CANADA

VERIFYING A FISSILE MATERIALS CUT-OFF: AN EXPLORATORY ANALYSIS OF POTENTIAL DIVERSION SCENARIOS

DECEMBER 1994

CANADA

VERIFYING A FISSILE MATERIALS CUT-OFF:

AN EXPLORATORY ANALYSIS OF POTENTIAL DIVERSION SCENARIOS

DECEMBER 1994

PREFACE

The genesis of this research project was the consensus United Nations General Assembly Resolution 48/75L of 16 December 1993 calling for a non-discriminatory, multilateral and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other nuclear explosive devices. Discussions are currently in progress to establish negotiations on such a "cutoff" treaty. At this time, the scope and nature of the prohibitions to be contained in the treaty are not agreed, nor are the consequent verification requirements entirely clear.

To better understand the verification aspects of a "cutoff" treaty, an analysis of possible diversion scenarios was undertaken under the Department of Foreign Affairs' Verification Research Program. The results of this analysis are not intended to be definitive; rather, they give an initial indication of the utility of the model and analytic procedure used, as well as provide a preliminary insight into the verification implications of a "cutoff" agreement. More accurate and detailed findings, potentially of greater operational utility, could be obtained by undertaking new iterations of the analysis that employ improved data.

The preliminary findings of this "bottom-up" analysis indicate that potential cost-savings for both the IAEA and individual national verification bodies could emerge from an evaluation of the frequency of inspections (and other verification activities) in terms of their relative value in reducing diversion risks. This prioritization process could improve verification cost-effectiveness.

The Department of Foreign Affairs and International Trade wishes to acknowledge the work performed in the preparation of this report under contract by David J. Winfield and Robert H. Campbell of Atomic Energy of Canada Limited, Chalk River Laboratories.

TABLE OF CONTENTS

List of Analysis Tables:

List of Figures:

Executive Summary

This report is a preliminary exploration of potential diversion paths relevant to a fissile materials "cut-off" agreement and the implications of these paths for verification. It is intended to provide background research material to be used in preparation for discussions on such an agreement.

An analysis framework is provided which gives information on the variables contributing to the risk of potential diversion paths for nuclear weapons fissile material. An extensive, systematic list of potential diversion paths, covering both declared and undeclared sources of fissile material, is provided. From this framework, relative risks for potential diversion paths have been assessed and defined for three generic groups of states: nuclear weapons states (NWS), developed non-nuclear weapons states (NNWSD), and undeveloped non-nuclear weapon states (NNWSU). A simple yet effective method is used to provide the common relative risk ranking scale. This method is specifically designed to accommodate judgements involving many subjective variables, and can accommodate technical, economic and political factors that are particularly relevant in this type of application. The judgements used in the relative risk assessment are those of the authors only. Wider input into the assessment process was not feasible within the resources of the project, but the method used provides the assessment information in a transparent form, readily available for review and scrutiny. The method used would be easily adaptable for a state-specific diversion-risk analysis.

The framework also provides a logical structure from which a more detailed analysis of the risk- relevant variables (e.g., diversion signatures, diversion likelihood, verification techniques and verification effectiveness) could be made. Cost aspects of verification are not discussed, but the systematic framework provides a logical way of incorporating this feature if required.

Technical developments can make current risk assessments invalid. Advances may be made with obsolescent fissile material production techniques, which make them viable and attractive, and novel techniques may be developed. Uranium enrichment technologies, in particular provide a good historical example where significant advances have been continually made. Without access to classified information it should also be recognized that open literature sources on this subject should be used with caution. There are examples in the available literature of contradictory information, in particular with regard to nuclear material specifications and what is, and is not, possible for weapons design. At the level of detail provided in this report uncertainties in material specifics and in verification technique specifics should not, however, influence the risk ranking conclusions presented.

The dominant diversion risk for NWS is judged to be from existing weapon-grade material stockpiles of both U-235 and Pu-239. Verification methods for stockpiled material should be straightforward, using existing methods. These methods can be expected to provide effective verification, providing that storage methods are well defined and the number of locations are limited. The potential diversion risk of stockpiled material not being declared prior to a cut-off agreement would, however, be significant. The next highest risk is judged to be from newer U-235 enrichment techniques under development and laser isotope enrichment in particular. These pose a short term risk in that knowledge of the current status of these techniques is unlikely to be divulged for proprietary reasons. They also pose a longer term risk in that the techniques are eventually likely to be obtained by less developed states. Diversion signatures and associated verification methods for these newer techniques including laser isotope, whether declared and undeclared, are also not currently defined nor used.

For the NNWSD, diversion from existing stockpiles of both U-235 and Pu-239 (declared or undeclared) also ranks as high risk, but with the laser isotope, gas centrifuge and aerodynamic U-235 enrichment methods judged as somewhat higher risk. Safeguard techniques for declared facilities of these latter two (demonstrated) methods are used but these methods, in

isotope, gas centrifuge and aerodynamic U-235 enrichment methods judged as somewhat higher risk. Safeguard techniques for declared facilities of these latter two (demonstrated) methods are used but these methods, in particular, have features that make them vulnerable for clandestine HEU production in declared facilities licensed to produce low enrichments. It is also quite possible that the existence of undeclared enrichment facilities of these types could remain unidentified with existing technical means of verification alone. Only special inspections could confirm potential production capabilities of undeclared facilities of this nature, once they had been identified.

For the undeveloped non-nuclear weapon states (NNWSU), the dominant risk from undeclared sources is judged to be from clandestinely obtained weapon-grade or adequately enriched material, in some chemical form, for both U-235 and Pu-239, obtained from offshore sources rather than from indigenously-developed facilities. Verification of this type of diversion path would have to be obtained primarily from various sources of intelligence information. Electromagnetic, gas centrifuge and the aerodynamic U-235 enrichment techniques pose the next highest potential diversion risks for undeclared U-235 diversion path facilities and the highest for declared facilities. No declared electromagnetic facilities, (considered relatively low technology) and associated verification techniques currently exist. Verification aspects of declared or undeclared gas centrifuge and aerodynamic enrichment facilities would be the same as noted above for the NNWSD. Assessed as medium risk for undeclared U-235 facilities was the thermal diffusion enrichment method. This method, similar to electromagnetic enrichment, is currently ignored by developed states but could have some advantages for clandestine U-235 enrichment by NNWSU. For the Pu-239 diversion path, research reactors are the highest risk for declared facilities. Existing safeguard methods provide effective verification for research reactors, although reactor-specific safeguard resources would vary with research reactor design. For undeclared Pu-239 the risk of material obtained from smuggled sources is judged the highest, as already noted.

A verification strategy should not focus entirely on the high risk diversion scenarios identified, nor entirely on the effectiveness of a specific-facility verification technique. This type of verification regime may well result in states, with the intent of diversion, choosing paths where verification methods are not available or not applied. For non-nuclear weapon states these clandestine diversion paths might be of low efficiency, or quite different from those that a technically developed nuclear weapon state would contemplate. Smuggled acquisition, by offshore purchase or theft and the use of thermal diffusion enrichment technology are examples that may well be pursued. A verification regime covering a wide range of possible diversion scenarios, particularly those relevant to the identification of potential undeclared facilities, that currently have no existing safeguards or verification methods, is recommended. Verification methods for these undeclared facilities will primarily use technical means including various types of intelligence information, combined, when detection confidence is high, with special inspections to provide confirmation of the undeclared facility purpose. Intelligence information alone, obtained from remotely detected diversion signatures, would not in general be expected to confirm facility production capacities. A cut-off agreement should also have sufficient flexibility to be able to implement verification methods for material acquisition that are being, or may be, developed for potential future production. This would mean that the existing safeguards systems for declared facilities, of routine inspections verifying materials accounting, containment and in situ surveillance, should be strengthened by continual development.

An optimum verification regime for a given material route is not defined in this report but the analysis approach could be used to provide the technical basis for optimization, based on the generic definitions of state types. Assessment of state-specific diversion risks and an associated optimum verification regime could also be provided using this analysis approach.

List of Acronyms

AS	Aerodynamic Separation Method
DCDPDNWF	Declared Civilian, Dual Purpose or Dedicated Nuclear Weapon Facilities
DFAIT	Department of Foreign Affairs and International Trade
EM	Electromagnetic Enrichment Method
GD	Gaseous Diffusion Enrichment Method
GC	Gas Centrifuge Enrichment Method
HEU	Highly Enriched Uranium
IAEA	International Atomic Energy Agency
LEU	Low Enriched Uranium
LIS	Laser Isotope Separation Method
NPT	(Nuclear) Non-Proliferation Treaty
NNWSD	Non-Nuclear Weapon States, Developed
NWS	Nuclear Weapon States
NNWSU	Non-Nuclear Weapon States, Undeveloped
R &D ENR	Enrichment Techniques at R & D Stage
RTR	Research/Test Reactors
TD	Thermal Diffusion Enrichment Method
TM	Technical Means
UCl4	Uranium Tetrachloride
UF6	Uranium Hexafluoride
UN	United Nations
UNGA	United Nations General Assembly
UNSSD	United Nations Special Session on Disarmament
UNWF	Undeclared Nuclear Weapons Facilities

1. Introduction

In December 1993 the United Nations General Assembly produced a consensus resolution containing a call for a non-discriminatory, multilateral and effectively verifiable treaty on the production or cut-off of fissile [1] materials for nuclear weapons and for nuclear explosive devices used for non-military purposes. Proposals for the cut-off of fissile material production have, in some form, been on the international arms-control agenda since just after the use of nuclear weapons against Japan in 1945, but have never been implemented into a treaty.

A number of contributing geopolitical realities have now made the prospect of a cut-off treaty a serious option as an arms control measure. Among these realities are concerns over a repeat of the nuclear weapons program similar to that of Iraq, in North Korea and elsewhere. The security of the stockpiles of fissile material in the new states of the former USSR and the existence of excessive stockpiles of fissile material already produced by the major nuclear weapons states are also current concerns.

This report is intended to provide background research material to be used in preparation for discussions on a cut-off agreement. To provide insights into these verification aspects a systematic fissile material diversion threat/risk analysis is presented. This provides a global perspective by documenting all credible material diversion threats from facility types and other acquisition sources. From these threat paths an assessment is then made of the overall risk, to final weapon-grade material production, posed by a given type of diversion. Specific verification techniques are then systematically identified from the various diversion path signatures documented in the analysis tables. The verification techniques appropriate to the highest diversion risks can then be identified.

2. Objectives

This report comprises:

(a) A bibliography of the unclassified literature on fissile material cut-off and verification aspects, together with a content summary of the more recent references, judged to be the most relevant and informative on the subject.

(b) A summary of the history of various cut-off initiatives with associated references.

(c) A threat/risk assessment, systematically listing the potential generic diversion paths of fissile material from the following:

- known nuclear weapons facilities, dedicated to fissile material production for nuclear weapons,

- civilian facilities that produce weapons-grade material for non-nuclear weapons purposes and civilian nuclear fuel-cycle facilities that could produce weapons grade material if desired, or facilities specifically designed for a dual-use purpose, and

- clandestine nuclear weapons facilities and fissile material acquired clandestinely.

---

[1] Fissile isotopes are defined as those that can sustain a fission chain reaction with fast neutrons.

The diversion path listing is intended to be as complete and systematic as possible, so that a global perspective covering all potential fuel-cycle facilities and other material acquisition routes may be gained. The listing is also chosen to capture the different potential diversion likelihood, according to types of states. The state categorization types are defined in Section 4.3.1. The state grouping is based on potential intent and technical capability to violate a cut-off agreement, rather than based on the NPT status of a state. Most literature, until very recently, has concentrated almost exclusively on the US/USSR situation, and tended to consider only those diversion paths focusing on the most up-to-date and developing technologies, which only a large nuclear weapons state would likely pursue. In addition, undeveloped non-nuclear-weapon states are unlikely to be pursuing the sophisticated nuclear explosive designs of the developed states, and it should be recognized that fissile material specifications that developed states would likely use could be substantially simplified from those used by developed states if only a very crude fission weapon (≈ 100 tons TNT) was the objective.

(d) A qualitative relative risk ranking for each diversion scenario as a function of state type. This is obtained by documenting and assessing the importance of specific characteristics of the variables that contribute to diversion risk. These variables are a combination of the likelihood of the diversion scenario and the importance of the diversion scenario to the final materials acquisition. Relative risk rankings of specific states are not provided, but the general framework used could be easily extended for this purpose.

The purpose of the threat risk assessment is to be able to identify and justify the dominant diversion risks and utilize this information in the formulation of a verification package for a cut-off agreement. While the diversion risk rankings are necessarily only qualitative and subject to uncertainty, the process of identifying the relevant variables and the subjective judgements used is visible and available for audit. Risk rankings on this subject are rarely discussed in the literature. As an example, a basic premise of Special Nuclear Materials safeguards to-date is that all nuclear materials, regardless of their importance in a potential weaponization process, are considered to require safeguards. The unclassified literature, prior to the Iraq example, for instance, also did not consider electromagnetic isotope enrichment as a credible diversion scenario. This report attempts to provide a systematic approach, identifying fissile material cut-off verification methods across a broad spectrum of potential diversion scenarios and relating them to a predicted scenario risk.

A simple example of proliferation relative risk rankings for specific U-235 enrichment facilities, based only on technical features of the processes, has previously been provided by Krass, [1983]. This current report expands upon this example considerably by showing how to include economic, political and social factors, in addition to technical factors, and by showing how a systematic decision analysis technique can be used to provide a single risk-ranking scale. The risk ranking of this report is also of much broader scope than that of Krass, [1983]; it covers all potential facilities (declared and undeclared) and material acquisition methods for all three isotopes relevant to the cut-off of fissile material.

3. Literature Search

A bibliography in Appendix A lists all recent and relevant review articles, provides an historical overview and provides detailed references on the various technical aspects of verification of fissile material cut-off. The list is provided in chronological order with the newest references first. The articles judged most relevant have vertical bar markers. A brief review summarizing the contents of some of the more relevant articles is provided in Appendix B. Some non-classified references providing specific technical information on nuclear weapons materials

have been provided in a second listing in Appendix A. Copies of the most relevant items have been obtained, together with other references on more technical aspects on fissile material and related production facilities. The articles are available from the authors on request.

The concept of halting the production of nuclear weapons fissile material, primarily plutonium-239 and highly enriched uranium, dates back to 1946, when the US presented the Baruch Plan to the UN. This plan proposed a concept for complete managerial control of the production of fissile materials. The bibliography of Appendix A and B does not include a complete list of proposed resolutions presented at the UN, from the US or other member states on the subject of cut-off. Some of the more recent references in Appendix A do, however, provide specific details of the key cut-off proposals. Appendix C also provides a brief historical review of cut-off and related proposals for reference.

4. Analysis Method

This section discusses the way in which the data specified in the Section 2, items (c) and (d) are documented. A spreadsheet-type representation is used to present this information in Tables 1.1 to 1.3 and Tables 2.1 to 2.3. These six tables summarize a complex picture of various potential fissile material diversion paths, diversion signatures, verification techniques appropriate for declared facilities, undeclared facilities and undeclared acquisition routes. This data is then assessed to provide relative diversion-risk rankings, according to different types of states. Treaty implications across the whole spectrum of relevant facilities and fissile isotopes can then be seen in overview.

The framework is also intended to provide a systematic logical structure from which a more detailed analysis of any of the items could be made, without changing the method of representation. Tables 1.1 to 1.3 deal with declared facilities and Tables 2.1 to 2.3 with undeclared facilities. The fissile materials relevant to a production cut-off agreement determine three isotope-specific diversion routes: U-235, Pu-239 and U-233 (see Section 4.1.1). Each of these three isotope routes are then separately represented for both declared and undeclared facilities. Other fissile isotope routes to weaponization are, in principle, possible (see Section 4.1.1). These latter routes are not considered credible in the foreseeable future, for either developed or undeveloped states, and so have not been included in the analysis.

The tables list across the top the potential facilities or material acquisition methods. This listing is provided as systematically as possible to ensure completeness and the rationale is discussed further in Section 4.2. Down the left side of the tables are variables which provide information relevant to the assessment of relative risk of material diversion for each potential facility type. Sections 4.3.1 to 4.3.6 define and discuss each of these risk-relevant variables. As diversion risks are also expected to be strongly dependent on individual states, the way in which these are included in the tables is discussed in Section 4.3.1.

4.1 Fissile Material Diversion Routes

The following sections discuss the rationale for the choice of the fissile isotope materials and the associated sources of potential diversion paths, which are represented across the top of the six analysis tables.

4.1.1 Fissile Material Type

The only fissile isotopes from which fission weapons have been made to date, [Appendix A, Bibliography references (i), (ii), (iii), (iv), (v)] are U-235, U-233, and Pu-239. Other plutonium isotopes, or mixtures of plutonium isotopes involving Pu-240 to Pu-243, are also technically feasible. The technical disadvantages and production disadvantages of the latter isotopes are such that their use can be considered as extremely improbable, and they are not specifically considered in this report. The data presented here for Pu-239 would, however, also be generally valid for other plutonium isotopes.

The specific purity requirements for the three isotopes identified for practical weapons is not discussed (e.g., what is meant by weapons-grade plutonium). At the level of detail discussed in the report this should not significantly influence the conclusions. As an example, it has been widely reported in recent years that the US has demonstrated a nuclear explosion with reactor-grade plutonium. Other sources have disputed this (New Scientist, April 9th, 1994, p. 430). Without access to classified literature sources, this and similar issues associated with fissile isotope specifications and associated weapons tests cannot be confirmed. Bibliography references (iv) and (vi) provide the most detailed technical descriptions of weapon material purity requirements that are available in the unclassified literature.

Tritium is also an important non-fissile isotope for the advanced weapons states, as it is used to boost the fission power from fissile isotopes and to provide a neutron initiator. Tritium provides the basis for a reduced size of weapon, thus increasing the variety of delivery systems that could be used. It also increases the weapon shelf life compared to non-tritium neutron initiator designs. Although tritium cut-off is not included in the scope of the current study, it is discussed briefly in Section 6 for completeness. Pure fusion-isotope-initiated nuclear explosive devices remain undeveloped, so that safeguards preventing the diversion of fissile isotopes would automatically prevent the production of thermonuclear explosives.

To simplify the information presentation, each of the three potential isotope diversion routes is dealt with in a separate table. Facility types that contribute in a similar manner to more than one isotope route have been noted by cross references in the tables.

4.1.2 Generic Diversion Route Based on Facility Declaration Status

Two generic diversion routes to weaponization for each of the three defined isotopes, based on the declaration status of facilities, are defined to be:

(i) declared facilities, and

(ii) undeclared facilities and other undeclared fissile material acquisition methods.

In this report the term declared is intended to refer to facility status following a cut-off agreement and assumes that existing known weapons facilities are put under safeguards similar to the 'declared facility' status of current International safeguards.

These two generic routes are separated because the diversion risks and appropriate verification methods to confirm a fissile material production cut-off are, in general, quite different.

The declared facilities could logically be divided, according to the intent of the facilities, into:

(a) declared nuclear weapons facilities that are dedicated to fissile material production for nuclear weapons,

(b) declared civilian facilities that produce weapons-grade material for non-nuclear weapons purposes and that could also produce weapons-grade material for weapons purposes if desired, and

(c) declared dual-use facilities specifically designed and operated to produce military-use weapons-grade material, as well as non-military-use weapons-grade material.

All these types of declared facilities would then, in principle, require some measure of verification, in order to confirm compliance with a fissile material production cut-off treaty if the potential diversion risk was assessed as sufficiently high. The types of facilities in these three groups are technically very similar. The verification/safeguard methods are also not as distinctly different from those needed to detect undeclared facilities, although there is a difference between the verification needs for monitoring military facilities that might be shutdown as a result of a cut-off treaty (e.g., a dedicated Pu-239 producing reactor) and an operating dual-purpose civilian facility (e.g., the Chapelcross reactors in the UK). The declared facilities are identified separately, but the relevant data is presented in the same set of analysis tables, see Tables 1.1. to 1.3.

The designation used for the declared facilities is Declared Civilian, Dual Purpose or Dedicated Nuclear Weapons Facilities (DCDPDNWF) and that used for the undeclared facilities, Undeclared Facilities (UF). The analysis tables for DCDPDNWF are Tables 1.1 to 1.3 and for UF are Tables 2.1 to 2.3. The three tables in each of these groups then correspond to the potential fissile isotope diversion routes defined in Section 4.1.1.

4.2 Facility-Specific Diversion Route or Source of Material Acquisition

The various facilities, or material acquisition sources, that may potentially contribute to the production and acquisition of the three fissile material isotopes are listed across the top of the tables and are discussed in the sections below for each isotope. The listing is generally in the order of the progression of the civilian or military fuel-cycle route needed to achieve an adequately pure fissile isotope for weapons use. [2] While some facilities may or may not be located on a separate site (e.g., uranium conversion may be at a mill or at an enrichment facility) each process is still listed separately, because the diversion signature will generally be unique to a type of production process, rather than a specific location. In this way, potential diversion during transfers of material between facilities may then be identified if transport diversion signatures (Section 4.3.3) are significant.

4.2.1 Uranium-235 Route

Tables 1.1 and 2.1 represent the various potential diversion paths relevant for the U-235 acquisition route for declared and undeclared facilities, respectively. The key to this route is enrichment of natural uranium. The main features of this route, compared to the Pu-239 route, are that facilities with minimal radioactivity concerns are involved and that the enrichment process is, in principle, technically much more difficult and expensive than

[2] Where a number of different techniques exist that can be used for the same function (e.g., U-235 enrichment), the list moves in general from the simplest/oldest technology to the most advanced/newest technology.

extracting and reprocessing plutonium from irradiated reactor fuel. The radioactivity is only that from natural uranium, which is relatively minor. There are also nuclear-criticality aspects of the final production stages, associated with some enrichment techniques and also with the handling and storage of highly enriched kilogram quantities of the final product. Nuclear-criticality problems are also associated with kilogram quantities of the other weapons-grade fissile isotopes.

Potential acquisition via smuggled material is included under the undeclared facility category, as this source cannot be discounted. While there has been no confirmed evidence of undeclared (clandestine) international shipments of high or weapons grade uranium or plutonium, this type of scenario is now considered quite plausible, [3] with particular regard to the current situation in the states of the former Soviet Union and the large quantities of weapons-grade fissile material now available. Smuggled material is here defined as being clandestinely obtained from non-indigenous sources by either undeclared purchase(s) or theft. The latter could potentially occur from materials in storage or materials being transported between facilities. There have, for example, been a number of recorded cases internationally of undeclared natural and depleted uranium shipments. [4]

A very large number of processes can in principle be used to separate and hence enrich uranium with the U-235 isotope. Only techniques known to have been demonstrated to at least a pilot-plant stage have been included in the diversion path analysis tables. For completeness, in the overall facility risk rankings all other techniques that are either at the R & D stage, considered either obsolete or at the possible-in-principle stage, have been grouped together, see Figure 2 (*R & D Stage* labelled box). A general discussion and listing of these techniques is provided in Krass, [1983]. The laser isotope techniques (molecular and atomic vapour), chemical exchange techniques and aerodynamic techniques are separated in the tables, as these have reached advanced stages of development in some states.

4.2.2 Plutonium-239 Route

Tables 1.2 and 2.2 list the various facilities relevant for the Pu-239 acquisition route for declared and undeclared facilities respectively. The key items for this route are reactor irradiation of, primarily, low enriched or natural uranium, [5] followed by extraction of plutonium from the spent reactor fuel using a plutonium reprocessing plant. The main features of the route then require a power/production or research reactor and a reprocessing facility, the latter of which involves the handling and storage problems of highly radioactive liquid wastes. The extraction of plutonium, while involving highly radioactive materials, is considered to be technically much easier than uranium enrichment, although a reactor to produce irradiated fuel

---

[3] An attempted clandestine sale in 1993 of Russian weapons-grade Plutonium has recently been reported [Economist, 25/12/93, p.67], and a 1993 theft of 1kg of HEU (subsequently recovered) from a Russian site was also reported [Time, 18/4/94 p.31]. The extent of this particular risk was highlighted in a recent editorial [Science, Vol 263, March 18, p.1543, 1994] and also in detail in: Capitol Hill; Congressional Testimony, June 27th, 1994, of T.B. Cochran before the Committee of Foreign Affairs Subcommittee on International Security.

[4] Nuclear Materials Management, 34th Annual Meeting, Scottsdale, Arizona, July 1993, p.305.

[5] Conversion of U-238 to Pu-239 using neutrons obtained from high-current proton accelerators, as an alternative to reactor irradiation of uranium, is also quite feasible [Accelerator Production of Tritium, Executive Report, Brookhaven and Los Alamos Laboratories; BNL/NPB-88-143, March 1989], but is discounted for this study as demonstration accelerators for this purpose have not yet been built.

containing plutonium has also to be available. Plutonium is however more difficult to process into final weapons-grade chemical form than uranium.

As with the U-235 route, the possibility of smuggled plutonium [3] is included in the undeclared facility category.

4.2.3 Uranium-233 Route

Tables 1.3 and 2.3 represent the various facilities relevant for the U-233 acquisition route for declared and undeclared facilities respectively. The key items for this (thorium fuel cycle) route are production by reactor irradiation of naturally occurring Th-232, followed by the separation of U-233 from reactor spent fuel in a reprocessing facility. This route is much less likely than the previous two, because of the more complex and currently unused thorium fuel cycle, and also because U-233 and associated isotopes are more radioactive than U-235, thus complicating weapon design. Nevertheless, the US is reported to have separated 1.4 tons of U-233, and to have tested a nuclear weapon using this isotope. [6] While this quantity is significant in terms of potential numbers of weapons producible, it is extremely small compared to the quantities of Pu-239 and U-235 currently available in the NWS.

Similar to footnote [5], this isotope may also be produced from accelerator sources using Th-232. This type of facility is discounted at present, as the technology has not yet been developed.

4.3 Diversion Risk Assessment

To provide a qualitative assessment of the relative risk of diversion from the various declared facilities, undeclared facilities and other acquisition sources, the associated risk- and verification-relevant parameters are defined in the first vertical column of the analysis tables. The intent is to document the two main contributors to diversion risk for each facility type: diversion frequency and diversion consequences.

The diversion frequency is assumed to comprise a combination of parameters that directly affect the likelihood of diversion (Section 4.3.1), and the effectiveness of diversion detection (i.e., verification and/or safeguards) methods (Section 4.3.5). By factoring in diversion effectiveness it is assumed that detection would, in effect, contribute to frequency reduction and hence risk reduction. This would be caused by the measures subsequently taken and/or the pressures and inconveniences caused by the international community, as a result of diversion discovery.

The diversion consequence parameter is represented by assessing the importance of a particular facility anomaly (Section 4.3.2) to the overall fissile material acquisition process.

The sections below define the diversion-risk-related parameters in more detail, and discuss the type of information documented for these parameters in the tables.

---

[6] IAEA Safeguards and Detection of Undeclared Nuclear Activities, R.J. S. Harry, Nuclear Materials Management, 34th Annual Meeting, Scottsdale, Arizona, July 1993, p.109.

4.3.1 Likelihood of Facility Anomaly (L)

A facility anomaly in this context is defined as an apparently abnormal condition (i.e. a potential diversion) which would require further investigation for resolution. [7] As the likelihood of a diversion would be expected to be quite different, according to the technical and political status of a given state, three different state categories have been defined. An assessment is then made of the relative rankings of diversion likelihood between the three state types, for each potential facility/material source diversion type.

The three state categories are:

- **Nuclear Weapon States (NWS)**

  - technically developed states with declared (or demonstrated) nuclear weapons and power reactor and nuclear research facilities.

- **Non-Nuclear Weapon States (Developed) (NNWSD)**

  - technically developed states with a power reactor program and/or nuclear research facilities and may have an existing undeclared nuclear-weapon capability or the potential to quickly develop such a capability.

- **Non-Nuclear Weapon States (Undeveloped) (NNWSU)**

  - relatively technically undeveloped states with no power reactor program, some limited nuclear research facilities and a possible undeclared nuclear weapon capability or requiring a time scale of a number years (≈ 5-10) to develop such a capability.

4.3.1.1 Method of Assessing Likelihood of Anomaly

The systematic decision analysis method, "Expert Choice™", is used to rank the likelihood of anomalies for facilities judged to be of high importance to the final material acquisition (Section 4.3.2). For facilities judged to be of relatively minor importance, the ranking is based on intuition only. The judgements used in this analysis are those of the authors only.

---

[7] In IAEA safeguards terminology an anomaly is usually defined as being uncovered by 'surveillance'. This refers to observation, by inspection or devices, to detect undeclared movements of material and equipment tampering and also includes information from material accountancy and any other source of intelligence collection.

The decision analysis method is discussed in Appendix D. It was designed specifically to assess subjective variables on a common scale using expert judgements, in this case to rank the relative importance of states with regard to diversion likelihood. Figure 1 provides the decision analysis hierarchy structure with the associated variables used in this particular application for anomaly likelihood. Verification effectiveness is included as a variable contributing to the likelihood, as noted in Section 4.3. A more detailed analysis than the present one would further define this particular variable, as well as the others, down into further sub-criteria.

The ranking of only three state types could be done without the use of a systematic method, by simply using intuitive judgement only and this has been used for the diversion paths of lower importance. Intuition, however, makes judgements of the relevant variables in a non-systematic way. As numerous factors contribute to the assessment of diversion likelihood, the use of Expert Choice™ in this application provides a logical and auditable basis for the rankings, which intuitive judgements do not provide. In addition, the framework of Figure 1 could be expanded, if required, to rank the relative trustworthiness of individual states, or to rank a larger number of state category definitions. For instance, if individual states were being defined, then, for example, the likelihood of particular U-235 enrichment technologies being associated with a specific state could be assessed. The choice of the state categories used in this report is based upon intent and capability to violate, rather than on NPT status. The NPT status of a state is implicitly accounted for as a sub-criteria category in Figure 1 designated as *"Political/Security Status"* .

The overall qualitative anomaly assessment (e.g., high, medium, low) is summarized verbally on the spreadsheet tables or referenced to Expert Choice™ histogram figure results. A description of the interpretation of the histogram results is provided in Appendix D, Section D4.

4.3.2 Importance of Facility Anomaly to Final Material Acquisition (I)

This variable assesses the qualitative importance of a given facility to the final acquisition of weapons-grade fissile material. This parameter then represents the consequence contributor to risk (Section 4.3). As facility importance is based almost entirely on a rather simple technical basis the judgements in this case were based on intuition, rather than on the Expert Choice method. For example, an anomaly in uranium enrichment or plutonium reprocessing facilities would be far more significant (to the ultimate production of weapons-grade material) than anomalies in uranium mines or uranium mills.

4.3.3 Diversion Signatures

For each potential facility or material acquisition source, the various potential signatures (identifiers) that could be used to identify a diversion scenario are listed. These could involve physical, chemical or nuclear characteristics. This variable does not contribute directly to facility diversion risk but, in order to logical identify appropriate diversion verification methods (Section 4.3.4) and subsequently judge verification effectiveness, it is essential to provide a systematic list of diversion signatures. The list of signatures for a given facility is prioritized, as far as possible, from the general and simplest signature to the more specific and most detailed signature.

For undeclared facilities, for example, facility location identification features are the most general, followed by facility function identifiers, operational/shutdown status identifiers and production capacity indicators. To simplify the table presentation the signatures have not been specifically grouped by type. Intelligence-gathering methods, such as communication

interception, export/import information monitoring and analysis of publicly available information, collectively termed intelligence information, are also taken as being potential signatures, in cases where more specific identification methods may not be available.

For declared facilities, the most general identifiers are those that determine the operational/shutdown status, followed by production capacity identifiers and then deviation-from-declared-intent identifiers. For production capacities, diversion signatures indicate only where facility physical changes could be used for production increases or product output modification. Increases in operating duty time, which could, in principle, apply to all facilities except those operating continuously (e.g., gaseous diffusion enrichment facilities), are not identified as signatures. Duty time anomalies are therefore assumed to be be implicitly verified in accountancy anomalies. As with the undeclared facilities, declared facility signatures have not been specifically grouped by type.

4.3.4 Verification Methods

From the identified diversion signatures (Section 4.3.3) a list of appropriate safeguards/verification techniques is provided. These are defined into three generic types of methods, varying from the least to the most intrusive:

- Technical Means (TM), [8]
- Routine Inspections (RI), and
- Special Inspections (SI). [9]

Specific verification techniques corresponding to these groups are listed in the analysis tables.

The Technical Means are non-intrusive methods and comprise reconnaissance satellite systems using either photographic, infrared, radar or electronic sensors, and radar and acoustic systems. Chemical and radionuclide environmental detection and monitoring methods and non-technical intelligence collection and analysis means are also defined as technical means for the purposes of this report. Remotely transmitted information from local sensor monitors (e.g. video camera) is included. A film camera requiring an on-site visit to retrieve and change film would, however, be considered a routine inspection technique. Intelligence information, as defined in Section 4.3.3, is also used in the analysis tables as a Technical Means method.

The Routine Inspection techniques are used as a part of existing, or potential, IAEA safeguards (e.g., on-site surveillance, containment and accountancy) which require the presence of a resident or non-resident inspector, using either off-site or on-site equipment to facilitate inspections using non-destructive or destructive analysis. Sampling, which involves off-site analysis, is considered to be destructive analysis, for example.

The techniques are listed according to the level of information provided. In safeguards diversion-verification terminology, increasing detection detail is defined by the terms gross, partial and small defects, although, as with the diversion signatures, the techniques listed have not been specifically categorized into those groups. The various safeguards accountancy and containment/surveillance verification methods available are very extensive (i.e., measurement types involve bulk, chemical assay and isotopic analysis, facility-specific operational process parameters and various seal type inspections). The specific methods vary considerably,

---

[8] These are also referred to in the literature as National or International Technical Means. For the purpose of this report, the ownership of the verification technique is not a concern.

[9] These are also sometimes referred to as unannounced inspections.

according to the facility type. To avoid excessive information the specific methods are not listed in the tables because of their very extensive nature and level of detail. A complete listing of all existing safeguard verification techniques is available from the IAEA Safeguard Manual, Chapter SMO 7.1, Annex 1, 1991. Potential verification techniques are listed for uranium mines and uranium mills for completeness, but uranium mines and mills are not currently safeguarded by routine inspection techniques. Only after yellowcake (U_3O_8) enters a uranium conversion facility are safeguards currently applied.

Special Inspections are as defined in INFCIRC/153, and would in principle include both destructive and non-destructive analysis techniques.

4.3.5 Effectiveness of Verification Methods

A descriptive qualitative assessment is provided of the effectiveness of verification methods, for a given facility diversion. The assessment is based on what is known of the current technologies. Intuitive judgement has been used for this assessment.

Verification method effectiveness is assessed for a specific facility diversion. There is no attempt to judge the combined effectiveness of verification methods on more than facility. The likely synergies from such an approach would provide insights into the verification effectiveness of detecting an overall fissile-isotope route diversion, as opposed to diversion in a single contributing facility. For successful overall diversion it is necessary to conceal, either the existence of, or the misuse, all the essential facilities over a period of time of a least a few years. The matrix type approach used in this report is quite suitable for a synergistic type analysis, which could be used, for example, to identify optimum verification strategies for a given fissile-isotope diversion route.

Cost-effectiveness aspects are not included. Aspects of verification where technically sensitive information from a commercial or national security aspect may cause problems for verification activities are not discussed. Aspects of verification activities that could provide information for potential violators to evade detection are also not discussed.

4.3.6 Risk of Diversion from Facility (L x I)

A qualitative relative assessment of the risk of diversion from each facility type is provided for each of Tables 1, 2 and 3. Information from the Likelihood and Importance items is utilized for this assessment, using the Expert Choice method. Figures 2 and 3 show the hierarchies used for the U-235 and Pu-239 isotope routes respectively. Figure 3 is also used for the U-233, route as it uses the same facility types as Pu-239. The facility diversion relative risk rankings are referenced from the analysis tables, and the presentation of the risk ranking format is the same as discussed in Section 4.3.1. Details on the pairwise assessments and the individual variable weightings are not included in the report, but are available from the author.

In Figure 2, the distinction between technically demonstrated and technically undemonstrated enrichment methods is not definitive, and is susceptible to change as technology develops. Techniques where the technical status is, from the unclassified literature, not definitive such as the laser isotope methods (MLIS and AVLIS), have been grouped under undemonstrated. The aerodynamic U-235 enrichment technique is intended to be the Helikon method, used by South Africa. This is placed under developed techniques, with the alternative aerodynamic technique, the jet nozzle, being included implicitly under *R & D Stage* defined techniques. The chemical exchange methods and mass diffusion technique (Table 1.1, footnote [1]) are also implicitly included under *R & D Stage* defined techniques.

As noted in Section 4.3.1, individual states are not assessed for specific facility risk. This is beyond the scope of the current report but the analysis structure provided could easily be expanded to provide this sort of detail.

5. Analysis Discussion

Tables 1.1/2/3, 2.1/2/3 and 3.1/2/3 summarize the diversion analysis risk-relevant information for the three material diversion routes. Figures referenced from the tables provide rankings, in histogram form, for the relative likelihood of facility anomalies as a function of state type, for some of the high importance facilities. The overall facility relative risks are similarly shown in the referenced figures in histogram form. The numerical order of the risk rankings is also provided for the three state types on the bottom rows of the tables. To aid interpretation the columns with vertical shading also highlight the dominant diversion paths for the state types. Sections 5.2 and 5.3 below summarize the results.

Comparison of the relative risk between each of the three potential material routes has not been systematically analyzed. To place the three isotope route risks in relative context the most important factors that influence the choice of fissile material route are summarized below.

From an availability viewpoint both U-235 and Pu-239 are much more likely than U-233 to be diverted, primarily because little U-233 has ever been made, and because of the complex thorium fuel cycle needed to produce it, in a reactor. In addition, the fuel reprocessing then needed to extract the U-233 and the subsequent radioactive handling of this material offer no advantages over the more widely developed plutonium production and extraction process.

The simplest weapon design uses the "gun" technique, where a sub-critical mass of material is shot down a tube into a similar subcritical mass. Either of the enriched uranium isotopes must be used for this type of device. Once available, then, U-235 is considered to be more attractive than Pu-239 to potential proliferators who have limited access to sophisticated bomb design technology. Plutonium cannot be used in a gun device, because a more rapid means of assembly of the critical mass is required, to prevent preignition, [Bibliography reference (vi), p.228]. Either Pu-239 or U-235 can be used in the alternative, implosion weapon design, which is more complex than the gun design. Less Pu-239 than U-235 is, however, needed in an implosion-type weapon. On the other hand, production of plutonium is technically less demanding than production of U-235, assuming a reactor facility for fuel irradiation is available, but Pu-239 does involve handling and storage of highly radioactive materials. While U-235 production is still very difficult, uranium enrichment is still a dynamic field, and proliferation assessment of developing, as well as older, enrichment technologies should be continuous.

5.1 Examples of Actual Diversion Scenarios

To illustrate where actual examples of attempted or successful material diversions have occurred with NPT signatory states, a list is provided below citing the Iraq and North Korean situations. These examples are cross referenced to the analysis tables, so that these diversion scenarios can be seen in context with other potential paths.

Iraq:

- yellowcake (U_3O_8) obtained from indigenous phosphate mine, (undeclared) — Table 2.1
- yellowcake obtained from foreign sources, (undeclared) — Table 2.1
- attempted acquisition of kg quantities of Russian made Pu-239, (undeclared) — Table 2.2
- development of calutron U-235 enrichment facilities (two separate locations), (undeclared) — Table 2.1

• development of chemical exchange U-235 enrichment, (undeclared)	Table 2.1
• obtaining gas centrifuge U-235 enrichment technology, (undeclared)	Table 2.1
• obtaining small amount of HEU from research reactor fuel, (declared source)	Table 1.1
• obtained 2 gm Pu-239 from reprocessing facility, (declared and undeclared)	Table 2.2 and 1.2

North Korea:

• research reactor fuel, special inspection denial of spent fuel accountancy system, potential Pu-239 route, (declared)	Table 1.2
• suspected undeclared Pu-239 reprocessing line in existing facility (declared)	Table 1.2

Footnotes [3] and [4] have also referred to other, isolated, cases of attempted diversions. A more extensive international list of facilities that were operating or under construction before being either announced or discovered has recently been provided. [10]

From the various facilities and material acquisition sources listed above, particularly with Iraq, what is indicated is the diversity of options pursued. Thus verification strategy should not be limited to selected declared and potential undeclared facility types assessed as high risk. Rather, verification should be broad in scope and developed in particular for potential undeclared facility paths. The revelation of the use of calutron enrichment by Iraq, in particular showed an intelligence failure because the likelihood of such a facility was not analyzed by looking at those special features of Iraq that made this technology a prime contender. Instead, judgements on safeguards implementation were made according to the needs of advanced states. Figure 1 has illustrated in principle how the relevant features can be systematically identified and assessed. In a similar way to calutrons, thermal diffusion enrichment for example, a known and practical technology, became obselete following its use during the Manhattan project and has received no attention by advanced states since then.

In addition to the example of the Iraq diversions, the large range of possible diversion paths and the required time scales set by various technologies also suggest that a broad scope verification strategy is desirable. This would ensure that verification that focuses on judged high-risk diversion paths did not result in encouraging the use of other paths, not selected for verification. For instance it is quite possible that the 1981 bombing of Iraq's Osirak research reactor prompted a change from a potential reactor/Pu-239 diversion program to the U-235 diversion program. This analysis identifies as low risk, facilities such as undeclared uranium mining for example but it should be recognized that a number of low-risk facility diversions can provide definitive evidence of intent, at an early stage. Therefore some minimal verification should be used for paths other than those judged as high risk.

5.2 Declared Facilities

5.2.1 U-235 Route

For the U-235 route the importance of an undeclared facility or material acquisition route anomaly to the final acquisition of material is qualitatively assessed in the second row of analysis Table 1.1. The most important diversion paths are enrichment processes and acquisition from existing enriched uranium sources. The first row of the table assesses the likelihood an anomaly according to each of the three defined state types. For three of the enrichment facilities, assessed with high importance, a detailed decision analysis was used to

---

[10] Bulletin of Atomic Scientists, June 1993, p.17.

rank the three state types. Results are shown in Figures 1.1.1a, 1.1.1b and 1.1.1c. Intuitive rankings were used to rank the rest of the diversion paths by state type. As noted in Appendix D, Section D4, the precision indicated by the decision analysis program output is not, in this application, justified, as the subjective judgements cannot in principle be accurate to three figures. The results, however, include data on all the main variables of Figure 1, and provide a logically derived ranking, which intuitive judgement does not.

The figures referenced from the bottom row of Table 1.1 provide the overall diversion-risk relative rankings as a function of state type derived from the hierarchy of Figure 2. For NWS and NNWSD the dominant diversion-risk potential for declared facilities (Figures 2.1.1a and 2.1.1b) are generally similar and are from existing stockpiles of weapons-grade material, the laser isotope separation technique, enrichment techniques under R & D and enriched uranium conversion/enriched-fuel fabrication facilities. The various techniques implied under R & D enrichment techniques are simply treated as a group but, as noted in Section 5, enrichment technology is dynamic and actual development progress may not be known. For example, the French development of the chemical exchange enrichment method was underway for nine years before it was revealed in 1977. Declared sources of HEU for use in research reactors or for naval uses are medium risk, because the fresh fuel material for them could be weapons-grade, and the physical volumes involved are not large. Gas centrifuge enrichment in particular has features that makes this method vulnerable for clandestine HEU production in declared facilities licensed to produce low enrichments and is assessed as somewhat higher relative risk for the NNWSD than the NWS. Safeguard techniques are used for verification of this type of facility and can be made quite effective but the basic process vulnerability remains. The safeguards involve more process equipment monitoring and calibration activities, compared to the more common materially-oriented safeguards used in other facility types. New design advances being made with gas centrifuges will greatly enhance the potential for clandestine HEU production if safeguard techniques are not upgraded.

For the NNWSU, Figure 2.1.1c shows quite different diversion risks than for the developed states. The electromagnetic (calutron) enrichment method, gas centrifuge enrichment method, aerodynamic separation and enriched uranium conversion/fuel fabrication facilities have the highest risk rankings. This analysis assumes that undeveloped states have a declared uranium enrichment program which in itself is quite unlikely and the only (declared) facility likely to be supported is a research/test reactor, although the aim could be self-sufficiency for fuel for future power-reactor projects. Currently there are no declared electromagnetic U-235 enrichment facilities and no safeguard program exists for them. The aerodynamic separation process currently has effective safeguards, but the discussion above regarding gas centrifuge misuse applies similarly to this technique. The medium risk from a declared research reactor would also depend upon its size, the nature of fuel and any isotope production program. The NNWSU are very unlikely to have declared advanced laser isotope or other R & D enrichment methods, so those paths are the lowest risks. Because of the unlikeliness of a declared enriched uranium program in a NNWSU, the overall risk of all the diversion paths from declared facilities would be expected to be much less than for declared facilities in the developed states.

For the verification methods listed in Table 1.1, a variety of existing safeguards routine inspection techniques are available for facility design, operations and inventory change verification for the known enrichment technologies, gas centrifuge and aerodynamic separation, and also for research reactors and conversion facilities. For the developed enrichment technologies and other existing facilities, identified as high importance, current routine inspections can provide adequate verification of diversion. As noted, safeguard techniques for gas centrifuge and aerodynamic enrichment methods need to be kept upgraded with advances in facility designs. Safeguard techniques remain to be developed for laser isotope and other enrichment methods under research and development.

5.2.2 Pu-239 Route

Table 1.2 provides an analysis for declared Pu-239 potential diversion paths similar to that described in Section 5.1.1 for the declared U-235 route. The diversion paths with the highest importance for final material acquisition, assessed in row 2, are dual-purpose and dedicated Pu-239 production reactor facilities for fuel irradiation, plutonium reprocessing (extraction) facilities and acquisition from existing declared weapon-grade plutonium sources. Intuitive rankings to assess the likelihood of facility anomaly by state type, row 1 data, were considered sufficiently simple that the decision analysis method was not applied in this case.

The figures referenced from the bottom row of Table 1.2 provide the overall diversion-risk relative rankings, as a function of state type. Figure 3 decision analysis hierarchy was used to derive these rankings; results are shown in Figures 3.1.2a, 3.1.2b and 3.1.2c.

For the NWS and NNWSD, Figures 3.1.2a and 3.1.2b, the diversion path risk rankings are basically the same. The diversion paths judged with the most overall diversion-risk potential are from existing weapon-grade stockpiles, plutonium reprocessing/plutonium fuel fabrication facilities, dual- use reactors, and research/test reactors. The risk from dedicated Pu-239 production reactors is small because the detection of facility clandestine operation (they would be shut-down as part of a cut-off agreement) would be conclusive from verification by relatively simple technical means.

For the NNWSU, Figure 3.1.2c, the dominant risks are research reactors and Pu-239 reprocessing/plutonium fuel fabrication facilities. An example of potential diversion using this route would be the recent concern over North Korea. Power reactors were excluded, by the definition of NNWSU, but were actually left in the risk rankings for illustration. The power reactor route risk would be expected to be low, as shown, again because of the ease of diversion verification, using spent fuel material accountancy.

Verification effectiveness, for declared stockpiles and dual-use and research/test reactors should be conclusive, as noted in Table 1.2, using existing safeguard techniques, primarily material accountancy and seal methods. Limiting the number of declared-stockpile locations, in particular, would maximize the effectiveness of these verification methods. Technical means alone would be very effective for identifying operation of declared production reactors. As noted above the reason for this is that the reactors would be shut-down under a cut-off agreement and the signatures of an operational reactor are very easy to detect. Diversion from plutonium reprocessing/conversion facilities is quite difficult to verify effectively using routine inspections, and special inspections do not provide any great advantage over routine inspections. A reprocessing plant is physically large and handles a large amount of fissile material in both solid and liquid form in continous processes. A complex accounting system requiring a significant, and continuous, inspection effort to audit is thus needed. Similarly the material accounting system of plutonium conversion/fuel fabrication facilities, which are smaller scale facilities than reprocessing plants, require significant effort to ensure that material balance uncertainties are acceptably small.

5.2.3 U-233 Route

Table 1.3 analyzes declared U-233 diversion paths in a manner similar to that described in the previous two sections. As discussed in Section 5, the U-233 route, in principle, is considered much more unlikely than both Pu-239 or U-235, for all state types. Material acquisition routes are the same as shown for Pu-239 in Table 1.2, reactor irradiation and fuel reprocessing/U-233 extraction being the key ones. The risk rankings of diversion paths would be expected to be the same as that of the equivalent Pu-239 facilities, Figures 3.1.2a, 3.1.2b and 3.1.2c, and

have not therefore been repeated. The verification assessment would also also be the same as for Pu-239, with specific analysis techniques for U-233 being substituted in place of Pu-239.

5.3 Undeclared Facilities

5.3.1 U-235 Route

For the U-235 route, the importance of an undeclared facility or material acquisition route anomaly to the final acquisition of material is qualitatively assessed in the second row of analysis in Table 2.1. The important diversion paths are enrichment processes and acquisition from existing enriched uranium sources. The first row of the table assesses the likelihood of an anomaly according to each of the three defined state types. For four of the enrichment facilities, assessed with high importance, a detailed decision analysis was used to rank the three state types. Results are shown in Figures 1.2.1a, 1.2.1b, 1.2.1c and 1.2.1d, as described in Section 5.1.1. Intuitive rankings were used to rank the rest of the facilities by state type.

The bottom row of Table 2.1 shows the overall diversion-risk relative ranking as a function of state type. Of the enrichment facilities, for NWS and NNWSD, the ones judged with the most overall diversion-risk potential for undeclared facilities (Figures 2.2.1a and 2.2.1b), are in order of risk ranking the laser isotope method, [11] the aerodynamic (Helikon) method and the gas centrifuge. Diversion using very large scale undeclared facilities, such as gaseous diffusion, is very small, as shown. This assumes however that a verification regime is in place to detect undeclared facilities, as it should be noted that footnote [10] indicated that an Argentinian gaseous diffusion plant remained undeclared, and undetected, for 5 years.

Enrichment techniques at the R & D stage are also high on the diversion risk list for the two developed state types for similar reasons, as explained in Section 5.1.1. Acquisition of enriched uranium from undeclared existing stockpiles is identified as the highest risk for NWS, and is highest after R & D and laser isotope facilities for the NNWSD.

For the NNWSU (Figure 2.2.1c) which have quite different diversion risks than the developed states, the highest undeclared diversion risks are from clandestine (smuggled) acquisition, via theft or the offshore purchase of raw or refined enriched uranium. If adequate quantities were made available by this route the large technical complexities of enrichment facilities could be bypassed. This assessment is a result primarily of giving a high weighting for the current political and economic situation, and the large quantities of fissile material, in the former states of the USSR. Enriched uranium conversion facilities, the electromagnetic (calutron) enrichment method and the gas centrifuge enrichment method then follow in the relative risk rankings. As expected, NNWSU with intent are more likely to use demonstrated than advanced R & D enrichment methods for the undeclared enrichment facilities route. This technology was one of those chosen by Iraq, Section 5.1, in its pursuit of the U-235 route to weapon acquisition. The thermal diffusion enrichment method is also identified, but at a somewhat lower risk. The importance of this latter method, considered obselete by advanced states, is that it was the method used in the US to make HEU for the first nuclear weapon and it provided slightly enriched feed for final enrichment by calutrons [Fox, 1945]. The method has

---

[11] The tables do not distinguish between the molecular or the atomic vapour method. The molecular method is usually quoted as being simpler and more prone to diversion, and this method is therefore implied. The atomic vapour method is implicitly included with the methods under R & D enrichment techniques in Figure 2.2.1.a, b and c.

long been discussed in the literature, [12] interestingly in a manner similar to calutron technology, as being obselete (for advanced states) but nevertheless as having some technical advantages, although only for small-scale enrichment programs. Advanced methods of enrichment were assessed as low risk from the NNWSU. As noted in Section 5, however, uranium enrichment is still a dynamic field. If the newer techniques that depend more upon the availability of chemicals and use well-established principles (e.g., chemical enrichment methods using solvent extraction or ion-exchange), as opposed to laser methods, are made available to undeveloped states, then the risk could change dramatically. As with the early dismissal by the developed nations of calutron technology, chemical enrichment methods were dismissed as being impractical for many years. However, the fact that developed states are taking many years to develop them, because in principle all enrichment methods are quite difficult, supports the current assessment of relatively low risk of newer techniques for the NNWSU. Denying access to existing technologies has nevertheless sometimes resulted in the successful development of indigenous technology, although undeveloped nations are only likely to acquire this technology, from sources in a developed state.

The only means of effectively verifying clandestinely obtained weapons-grade or enriched U-235 in some chemical form is by the use of intelligence information from various sources. Verification would be difficult because of the small quantity of material involved and because of the relative ease of handling the material, other than precautions to avoid criticality problems.

Verification of the existence of undeclared enriched uranium facilities is becoming more difficult, as facility sizes tend to decrease as equipment designs and efficiencies improve. Nevertheless, electromagnetic, gas centrifuge, aerodynamic and thermal diffusion facilities would still be fairly large and would have distinct signatures. It is expected that with current satellite and airborne monitoring techniques, and knowledge of the likely facility types, high confidence could be placed on identifying enrichment facility types of a known technology. Enrichment production capacities, however, would remain very uncertain, using surveillance technical means, unless alternative information, from routine, special inspections or other intelligence information, was available.

Verification methods to disclose undeclared uranium mining (including uranium mined from phosphate mines) and milling, or smuggled receipt of off-shore ore, would be expected to be conclusive. If access to the relatively small volumes needed of natural uranium concentrate were available, as a result of diversion from declared indigenous or undeclared offshore access, then technical means of verification of the uranium conversion process would be ineffective. Special inspections of natural and enriched uranium conversion facilities should be easily conclusive, provided the facilities could be correctly identified. Identification of a conversion facility would be very difficult, as the facility could be small and the nuclear emissions signatures would not be significant.

Diversion from undeclared research/test reactors is unlikely from any of the state types as the existence of these types of facilities is extremely easy to verify, although a facility located underground would be more difficult to identify.

While the diversion risk from mines and mills is low, because of the technically low importance to the final product, the use of potential verification techniques for undeclared

---

[12] Benedict, M. and Pigford, T.R., Nuclear Chemical Engineering, McGraw Hill Book Company Inc, 1957 Edition, p. 516.

uranium mines and uranium mills should still be considered a valuable part of a verification regime. These techniques would provide excellent and very effective signatures, indicating potential diversion at an early stage in any diversion attempt.

5.3.2 Pu-239 Route

Table 2.2 provides a similar analysis for the undeclared Pu-239 route similar to that described in Section 5.2.1 for the undeclared U-235 route. The most important facility anomaly diversion paths, row 2, are acquisition from smuggled enriched plutonium sources, plutonium reprocessing (extraction) facilities and reactors producing plutonium.

The bottom row of Table 2.2 provides figure references to the overall diversion-risk relative ranking as a function of state type. Figure 3 decision analysis hierarchy was used to derive these rankings, which are shown in Figures 3.2.2a, 3.2.2b and 3.2.2c. For the NWS and NNWSD the risk rankings are the same. The diversion paths judged with the most overall diversion-risk potential for undeclared facilities are from existing weapon grade stockpiles, dual-use reactors and reprocessing/fuel fabrication facilities. The risk from production reactors is small, because the detection of their operation is simple to conclusively verify by technical means.

For the NNWSU (Figure 3.2.2c), the dominant risk is acquisition of clandestinely obtained weapons-grade plutonium. Plutonium reprocessing facilities are assessed as the next highest risk diversion risk paths. Power reactors were exclude by the definition of NNWSU, but were left in the risk rankings for illustration, and would in any case be expected to be extremely low as shown, because of very unlikely existence of undeclared power, as well as, research reactors.

The only means of effectively verifying clandestinely obtained weapons-grade Pu-239 is by the use of intelligence information from various sources. This would be difficult because of the same reasons provided above for U-235. Pu-239 is somewhat more difficult to transport and handle but not significantly so. To determine the true nature of an undeclared plutonium reprocessing plant would also be difficult using optical or infra red surveillance technical means, as a small plant would not be physically distinctive. The radioactive signatures of Kr-85 and I-129 emissions from the facility, detectable by environmental sampling or monitoring, offer more conclusive evidence however. Verifying that undeclared production is actually being carried out and production rates could not conclusively be determined by technical means, and would require special inspections, which should be conclusive. The reprocessing operation might well not take place, however, until long after the first fuel irradiation was started in a reactor facility, depending upon the required time-scale for final weapons production. Verifaction of a undeclared research reactor should be straightforward unless it was underground but the actual production capacity would remain uncertain unless confirmed with special inspections.

5.3.3 U-233 Route

Table 2.3 provides the previously described analysis for the U-233 diversion route and associated facilities. As discussed in Section 5, this route, in principle, is considered much more unlikely than both Pu-239 or U-235 for all state types. Material acquisition routes are the same as those for plutonium, in Table 2.2, being reactor irradiation and fuel reprocessing/ U-233 extraction. The risk rankings of diversion paths would be expected to be about the same as that of equivalent Pu-239 facilities (Figures 3.2.2a, 3.2.2b and 3.2.2c), and have therefore not been repeated.

6. Relevance of Tritium to a Cut-off Agreement

The developed nuclear weapons states use tritium to boost the yield of their fission weapons and the fission triggers of their thermonuclear weapons. The efficiency and compactness of advanced nuclear weapons is achieved with the use of this isotope. Tritium is not, however, included as a nuclear material under the proposed cut-off treaty, so the potential relevance and implications of tritium cut-off are not part of this report. Tritium decays with a 12-year half-life, so if tritium replacement in weapons was cut-off, the number of weapons using it would necessarily be reduced in about a decade by about 50%. The fissile isotopes discussed in this report, by contrast, have half-lifes of thousands of years, which ensures that once adequate stockpiles are available, further production is unnecessary for replenishment. Plutonium weapons do periodically need reprocessing and rework to remove some undesirable radioactive-decay product buildup [Bib. ref (v)], but most of the material remains usable.

The radioactive decay of tritium is sometimes referred to as the tritium factor because of its important potential for reducing nuclear weapon stockpiles. Specific references discussing the implications of a tritium cut-off are provided in the following Bibliography references: [Lanouette W., 1989, Mark J.C., 1988; Wilkie T., 1984 and Epstein W., 1980].

7. Conclusions

7.1 General Comments

On the basis of this preliminary analysis, a verification package for a cut-off agreement would focus particular attention upon the dominant risks summarized in the sections below. As noted in Section 5.1 verification strategy should not be limited, however, to dominant risks, but should be broad in scope, in particular for potential undeclared-facility diversions. This would ensure that verification that focuses on high risk diversion paths does not result in encouraging the use of other paths, not selected for verification. The dynamic nature of an analysis of this type should be recognized, in view of ongoing technical and political changes. Verification methods for undeclared facility types are not currently part of the IAEA safeguards system but recent work at the IAEA is now putting into place a program to strengthen safeguards by developing undeclared-facility verification methods. These methods would primarily use technical means, including various types of intelligence information which, when detection confidence is high, combined with special inspections should provide confirmation of an undeclared facility purpose. In particular, methods to identify the potential existence of undeclared gas centrifuge, electromagnetic, thermal diffusion and aerodynamic U-235 enrichment facilities should be developed.

A cut-off agreement should have sufficient flexibility to be able to implement verification methods for material acquisition that are being, or may be, developed for potential future production. This would mean that the existing safeguards systems for declared facilities, of routine inspections verifying materials accounting, containment and in situ surveillance, should be under continual development.

Front-end fissile material diversion paths (e.g., acquisition of natural uranium ore from undeclared sources) should also receive attention, with a broad scope verification regime. This is because potential timeliness advantages may be gained from diversion identification at an early stage, despite the relatively low importance assigned to an anomaly in this type of facility.

Synergies between verification methods which could optimize verification cost and verification effectiveness are not accounted for. The analysis method presented could be readily adapted to provide this type of more detailed information.

7.2 Dominant Risks

The relative risk between three isotope routes is not explicitly analyzed. In the NWS, because of the huge material stockpiles of Pu-239 and U-235, there is likely no significant difference in risk between these routes.

For the NNWSU it is also likely that there is no significantly different risk between the two main routes if material is made indigenously and both routes may well be pursued together. U-235 is more difficult for undeveloped states to produce indigenously than Pu-239, although the latter requires a reactor facility. The existence of an undeclared reactor facility is relatively straightforward to detect, unless it is located underground, while undeclared U-235 enrichment facilities are, in general, harder to detect. In addition a U-235 'gun' weapon design is much simpler than a Pu-239 implosion weapon design. If the diversion is from smuggled sources, which is assessed as high risk for NNWSU, then U-235 would be more likely than Pu-239 because of its greater availability and easier handling.

The U-233 route should be a considerably smaller risk, for all state types, as it offers no significant advantages and has a number of disadvantages as discussed in Section 4.2.3.

The two sections below summarizes the dominant facility risks for the state types.

7.2.1 NWS and NNWSD

For NWS and NNWSD, diversion from existing material stockpiles, enriched uranium conversion facilities and laser isotope enrichment techniques, dominate the U-235 route for both declared and undeclared facilities. Enrichment techniques at the R & D stage all also judged as prominent from the Expert Choice outputs, but have not been included in the analysis Tables due to lack of specific data. For stockpiles the likelihood of diversion will increase with the number of storage locations. Once stockpiles are declared, verification with seals and camera surveillance, should be conclusive. Prior to the initiation of a cut-off agreement the risk of stockpiled material being kept in these states as undeclared would likely be very significant. Conversion facilities are relatively small size and involve a fairly simple process so that verification, of both declared and undeclared facilities, may not be conclusive. Verification techniques need to be developed for R & D stage enrichment facilities, in anticipation of commercial demonstration of these techniques.

The Pu-239 route risk is also dominated by existing material stockpile potential diversion and verification aspects are the same as noted for U-235. Existing international stockpile quantities are currently a few hundred tonnes of Pu-239 and many hundreds of tonnes of U-235. With potential undeclared stockpiles in mind, the development of new U-235 enrichment techniques is, in the shorter term not as important. However, with advances in technology the longer term risk is that these newer technologies become accessible to the less advanced states, who then continue their own development.

7.2.2 NNWSU

For the NNWSU, research test reactors and Pu reprocessing dominate the Pu-239 route declared-facility risks. Diversion from declared reactors should be simple to verify from routine inspections provided spent fuel accountancy records and seals are used. Verification of a declared plutonium reprocessing facility, particularly a small one, may not be conclusive unless very frequent inspections were used.

For the U-235 route declared facilities, electromagnetic, gas centrifuge and the aerodynamic enrichment methods, are the dominant risks. Verification using routine inspections can provide high assurances but methods used should be continually developed to ensure that both older and as well as developing technologies are adequately covered under the terms of a cut-off agreement.

For undeclared facilities, smuggled sources of either U-235 or Pu-239 dominate the risk followed by the same U-235 enrichment facilities as noted for declared facilities, and plutonium reprocessing/fuel fabrication facilities for Pu-239. Verification of an undeclared reactor facility should be conclusive although design and actual production capacities may be very uncertain. Despite radionuclide emissions a small undeclared reprocessing facility could also be difficult to identify and the production capacity could likely not be confirmed without special inspections.

7.3 Analytical Approach

The approach taken to collate the information acquired for this project, and the framework developed for the analysis and presentation of the material appears to be an innovative approach to this kind of problem. It is recognized that the information presented in this study has been developed from first principles, literature surveys, and limited discussions with technical staff, particularly regarding the risk ranking judgements. In essence, the study has been conducted with a relatively narrow support base. The framework, however, can serve as a viable platform for confirmation and refinement of the initial findings.

The main advantage of using this approach is that the dominant areas of concern are revealed in the analytical process and all of the bases for strategic decisions are auditable. Further development of the approach could incorporate cost-effectiveness aspects of the verification process if required.

8. Areas for Further Research

As a result of this study several areas for further work were identified, in refining and augmenting the current work and are listed below.

- The conclusions presented in the diversion risk rankings have been drawn from information in the existing, unclassified literature and from non-intelligence based sources. The decision analysis model structure and associated judgements used could be refined using input from a wider experience base.

- A state-specific diversion risk analysis could be developed and used by governments interested in ensuring that their non-proliferation policies and principles are being met.

- This report has taken an initial step in identifying the threats and risks associated with verifying a fissile materials cut-off regime. The potential benefits to pursuing this approach could be applied to other areas of arms control, disarmament and non-proliferation, such as chemical and biological weapons of mass destruction.

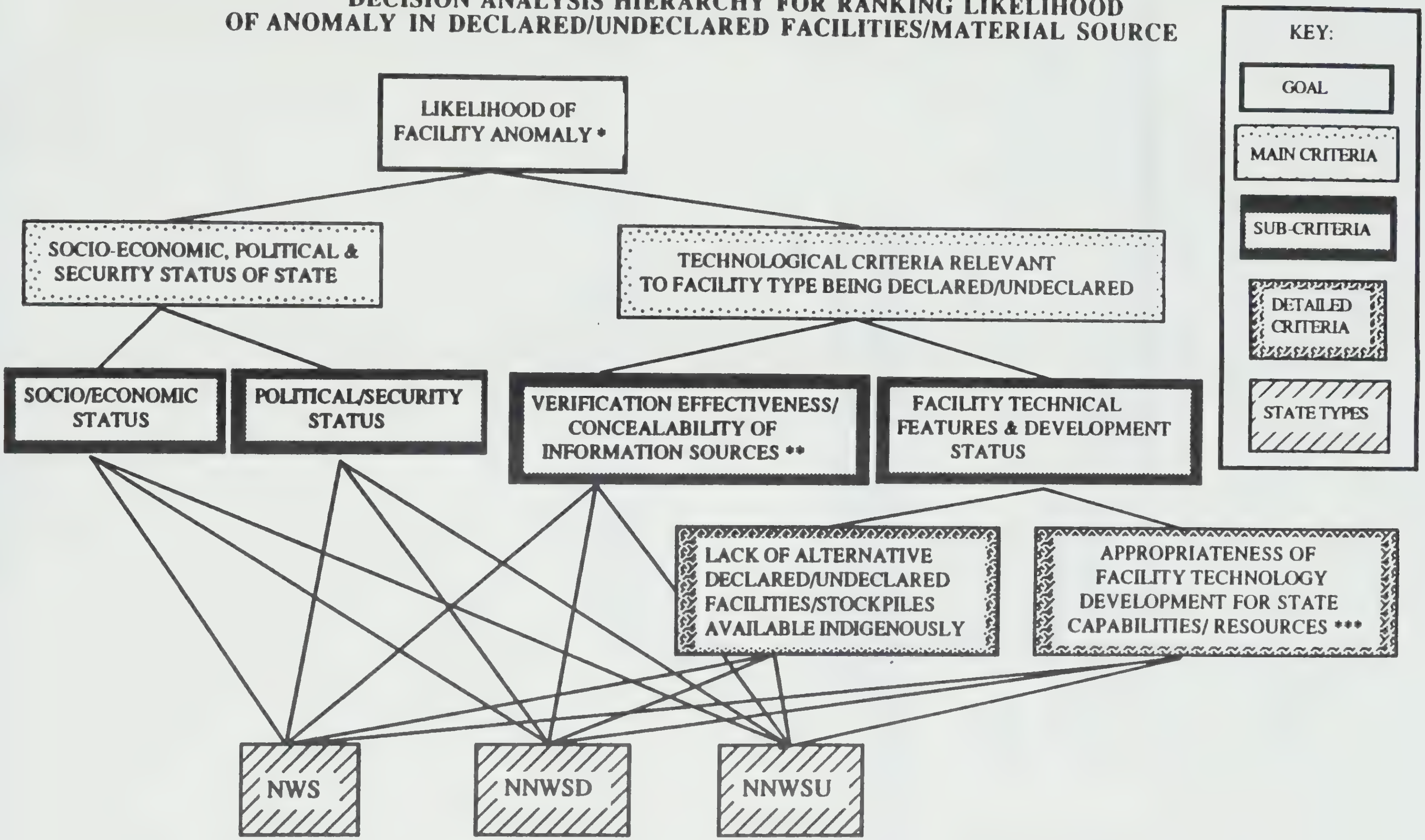
- An optimum verification strategy, accounting for both cost as well as technical effectiveness could be developed, for a given isotope path by looking at synergies from techniques applied to more than one facility. In particular, more detailed verification data than used in the current report would need to be produced.

- A data base of known attempted and actual diversion scenarios could be developed for use in validating judgements used and also to indicate potential diversion trends.

- Some research and discussion of the implications of tritium production in the context of the cut-off of production of fissionable materials would provide useful information for policy makers.

- Resources for safeguards strengthening should be focused on specific verification techniques of high diversion-risk contributors, including those recently identified for smuggled sources of acquisition. Some resources should still be extended to lower risk diversion scenarios so that the incentive to use these scenarios is maintained at a low level.

FIGURE 1
DECISION ANALYSIS HIERARCHY FOR RANKING LIKELIHOOD OF ANOMALY IN DECLARED/UNDECLARED FACILITIES/MATERIAL SOURCE



* The criteria that contribute to the likelihood of the specific type of declared/undeclared facility being used to produce nuclear materials.

** Typical information source categories are listed in the IAEA Safeguards Group country profile document, 1994 (e.g. environmental monitoring, IAEA technical assistance, IAEA travel reports.

*** Considers technical features suitable for large- or small-scale operation, economics and versatility.

C:\EC\FIG111A 05-04-1994 AECL Researc

RANKING OF STATE FOR LIKELIHOOD OF EM DECLARED FACILITY DIVERSION

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.04

NNWSD --- NON NUCLEAR WEAPON STATES DEVELOPED
NNWSU --- NON NUCLEAR WEAPON STATES UNDEVELOPED
NWS --- NUCLEAR WEAPON STATES

Figure 1.1.1a
State Relative Diversion Likelihood for Declared U-235 Electromagnetic Separation Enrichment Facility

C:\EC\FIG111B 05-04-1994 AECL Research

RANKING OF STATE FOR LIKELIHOOD OF GD DECLARED FACILITY DIVERSION

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.14

NNWSD --- NON NUCLEAR WEAPON STATES DEVELOPED
NNWSU --- NON NUCLEAR WEAPON STATES UNDEVELOPED
NWS --- NUCLEAR WEAPON STATES

Figure 1.1.1b
State Relative Diversion Likelihood for Declared U-235 Gaseous Diffusion Enrichment Facility

AECL Researc

C:\EC\FIG111C 05-04-1994

RANKING OF STATE FOR LIKELIHOOD OF GC DECLARED FACILITY DIVERSION

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.01

NNWSU	0.358	
NNWSD	0.348	
NWS	0.294	
	=====	
	1.000	

NNWSD --- NON NUCLEAR WEAPON STATES DEVELOPED
NNWSU --- NON NUCLEAR WEAPON STATES UNDEVELOPED
NWS --- NUCLEAR WEAPON STATES

Figure 1.1.1c
State Relative Diversion Likelihood for Declared U-235 Gas Centrifuge Enrichment Facility

C:\EC\FIG121A 05-04-1994 AECL Research

RANKING OF STATE FOR LIKELIHOOD EM UNDECLARED FACILITY DIVERSION

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.06

NNWSU	0.651
NNWSD	0.261
NWS	0.088
	=====
	1.000

NNWSD --- NON NUCLEAR WEAPON STATES DEVELOPED
NNWSU --- NON NUCLEAR WEAPON STATES UNDEVELOPED
NWS --- NUCLEAR WEAPON STATES

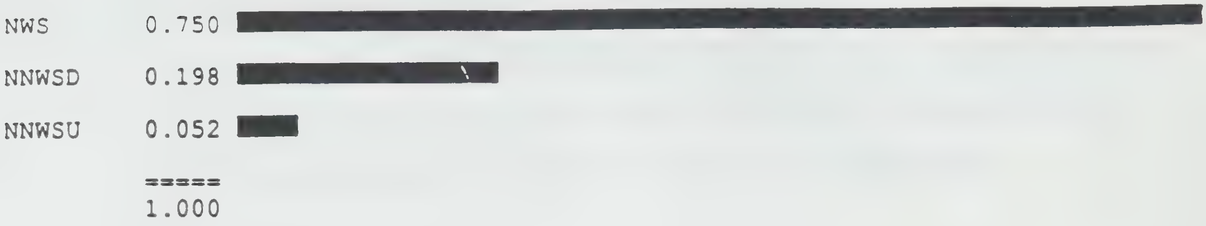
Figure 1.2.1a
State Relative Diversion Likelihood for Undeclared U-235 Electromagnetic Separation Enrichment Facility

C:\EC\FIG121B 07-24-1994 AECL Research

RANKING OF STATE FOR LIKELIHOOD GD UNDECLARED FACILITY DIVERSION

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.20



NNWSD --- NON NUCLEAR WEAPON STATES DEVELOPED
NNWSU --- NON NUCLEAR WEAPON STATES UNDEVELOPED
NWS --- NUCLEAR WEAPON STATES

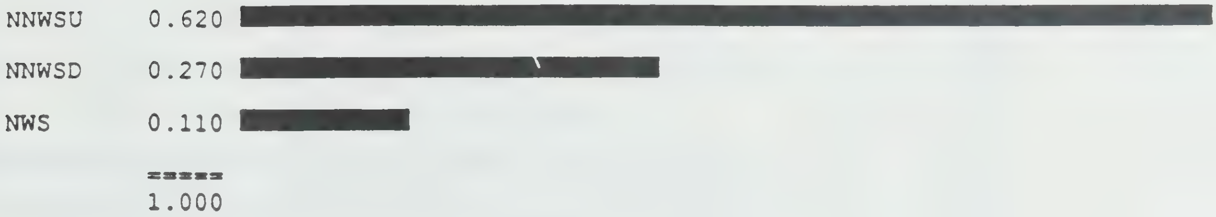
Figure 1.2.1b
State Relative Diversion Likelihood for Undeclared U-235 Gaseous Diffusion Enrichment Facility

C:\EC\FIG121C 05-04-1994 AECL Research

RANKING OF STATE LIKELIHOOD OF GC UNDECLARED FACILITY DIVERSION

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.01



NNWSD --- NON NUCLEAR WEAPON STATES DEVELOPED
NNWSU --- NON NUCLEAR WEAPON STATES UNDEVELOPED
NWS --- NUCLEAR WEAPON STATES

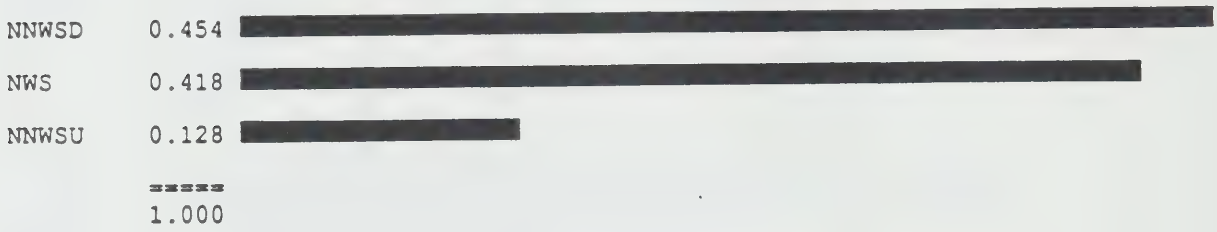
Figure 1.2.1c
State Relative Diversion Likelihood for Undeclared U-235 Gas Centrifuge Enrichment Facility

C:\EC\FIG121D 05-04-1994 AECL Research

RANKING OF STATE FOR LIKELIHOOD LIS UNDECLARED FACILITY DIVERSION

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.00



NNWSD --- NON NUCLEAR WEAPON STATES DEVELOPED
NNWSU --- NON NUCLEAR WEAPON STATES UNDEVELOPED
NWS --- NUCLEAR WEAPON STATES

Figure 1.2.1d
State Relative Diversion Likelihood for Undeclared U-235 Laser Isotope Separation Enrichment Facility

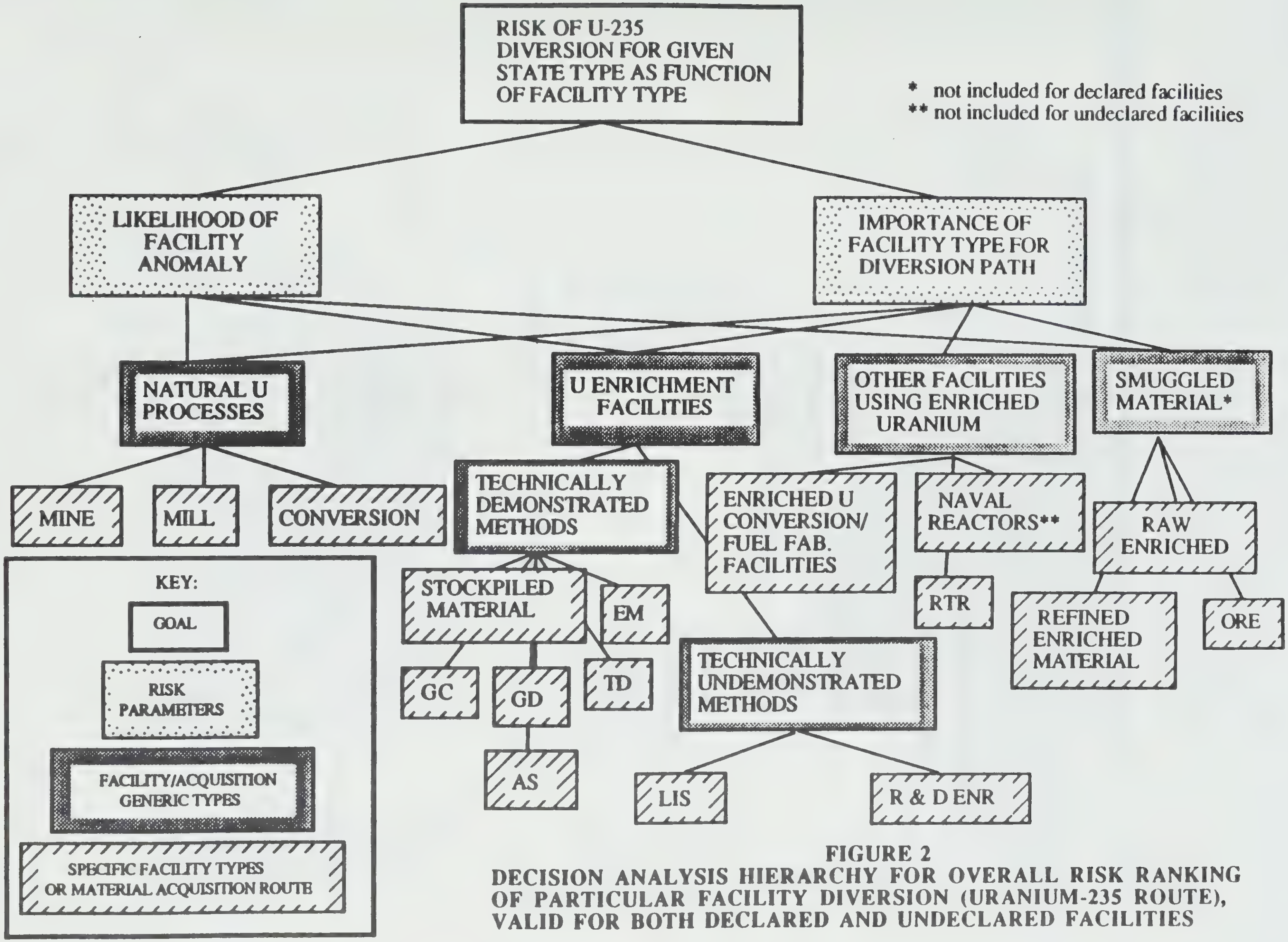
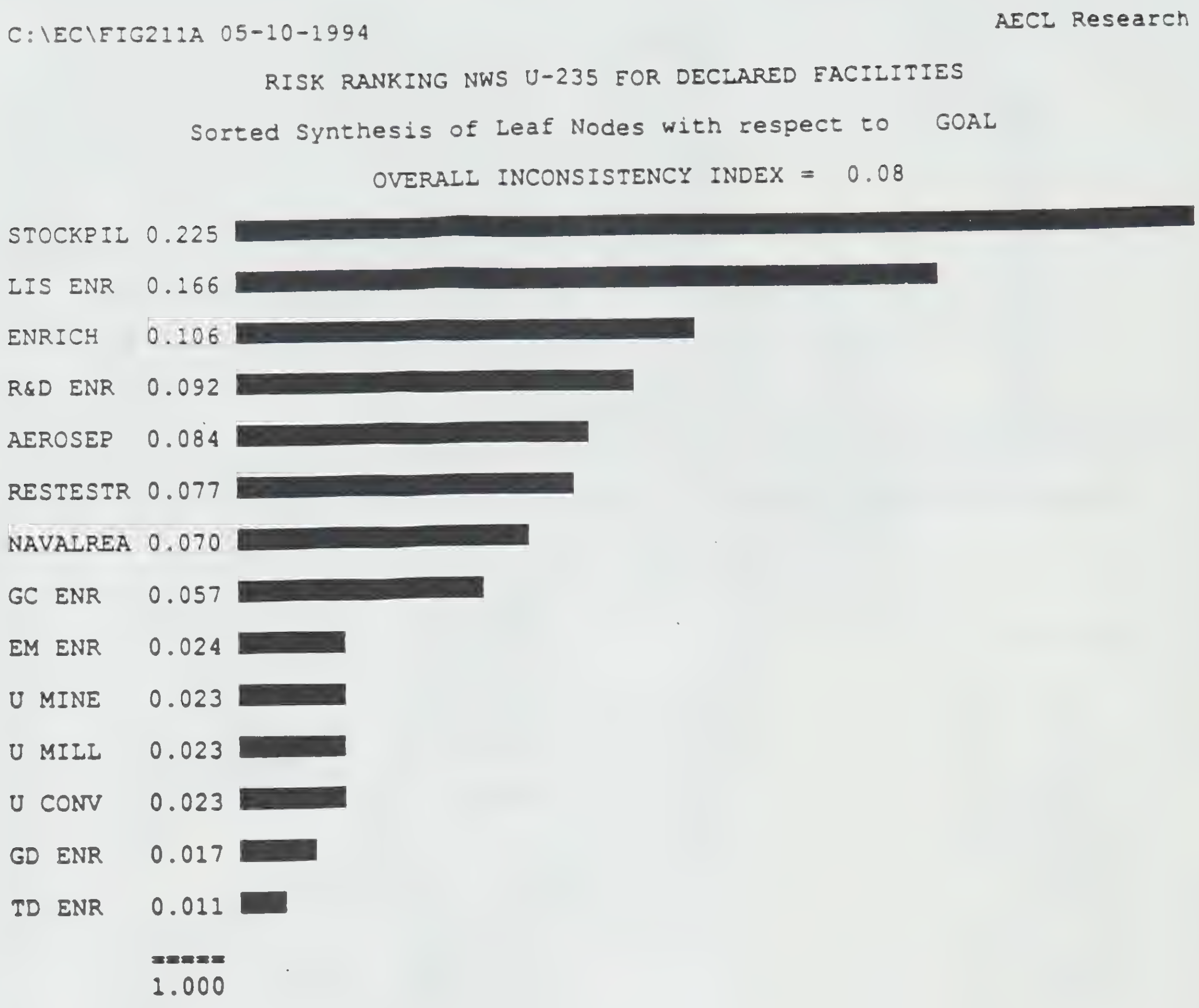


FIGURE 2
DECISION ANALYSIS HIERARCHY FOR OVERALL RISK RANKING OF PARTICULAR FACILITY DIVERSION (URANIUM-235 ROUTE), VALID FOR BOTH DECLARED AND UNDECLARED FACILITIES



AEROSEP --- AERODYNAMIC HELIKON SEPARATION TECHNIQUE
EM ENR --- ELECTROMAGNETIC ENRICHMENT
ENRICH --- ENRICHED U CONVERSION FACILITY/FUEL FABRICATION FACILITY
GC ENR --- HIGH SPEED GAS CENTRIFUGE ENRICHMENT
GD ENR --- GASEOUS DIFFUSION ENRICHMENT
LIS ENR --- LASER ISOTOPE ENRICHMENT
NAVALREA --- NAVAL REACTORS
R&D ENR --- ENRICHMENT TECHNIQUES AT R & D STAGE
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- ENRICHED U-235 MATERIAL AVAILABLE FROM STOCKPILES
TD ENR --- THERMAL DIFFUSION ENRICHMENT
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL
U MINE --- URANIUM MINE

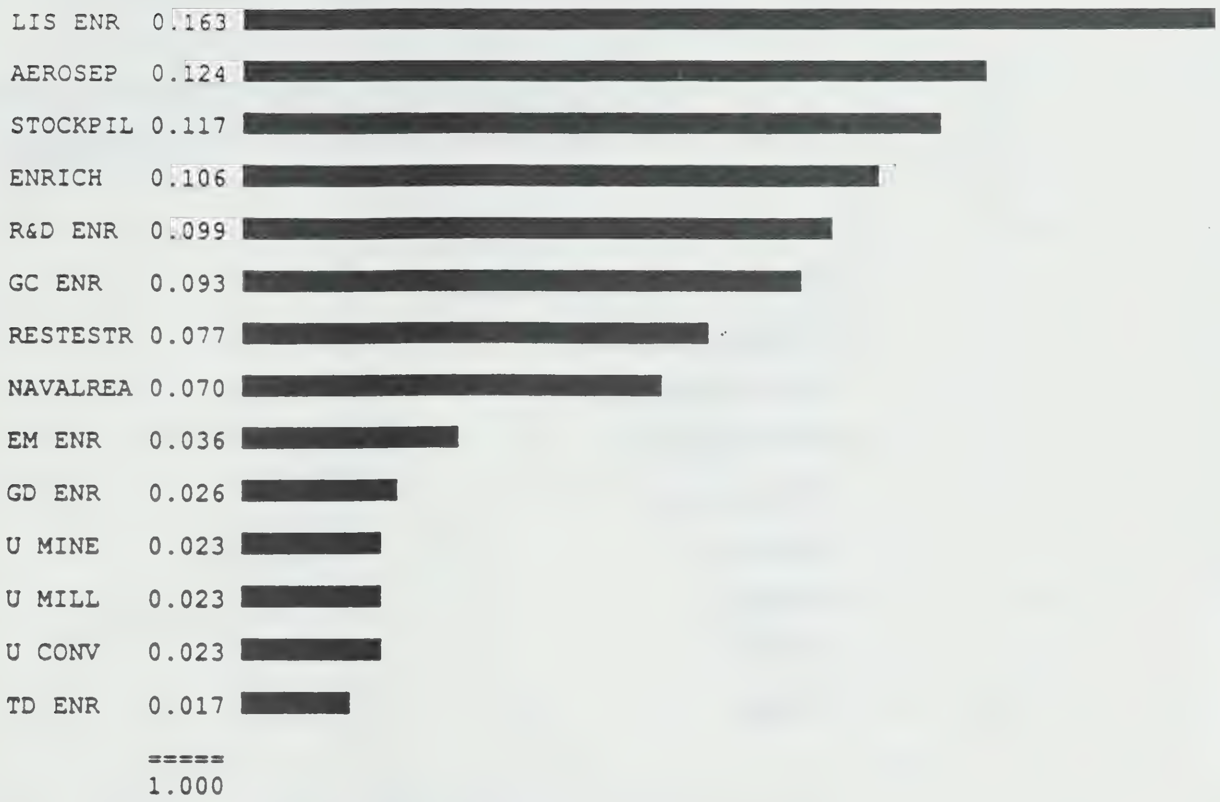
Figure 2.1.1a
Risk Ranking (U-235 Diversion) for Declared Facilities of a NWS

C:\EC\FIG211B 05-10-1994 AECL Research

RISK RANKING NNWSD U-235 FOR DECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.08



AEROSEP --- AERODYNAMIC HELIKON SEPARATION TECHNIQUE
EM ENR --- ELECTROMAGNETIC ENRICHMENT
ENRICH --- ENRICHED U CONVERSION FACILITY/FUEL FABRICATION FACILITY
GC ENR --- HIGH SPEED GAS CENTRIFUGE ENRICHMENT
GD ENR --- GASEOUS DIFFUSION ENRICHMENT
LIS ENR --- LASER ISOTOPE ENRICHMENT
NAVALREA --- NAVAL REACTORS
R&D ENR --- ENRICHMENT TECHNIQUES AT R & D STAGE
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- ENRICHED U-235 MATERIAL AVAILABLE FROM STOCKPILES
TD ENR --- THERMAL DIFFUSION ENRICHMENT
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL
U MINE --- URANIUM MINE

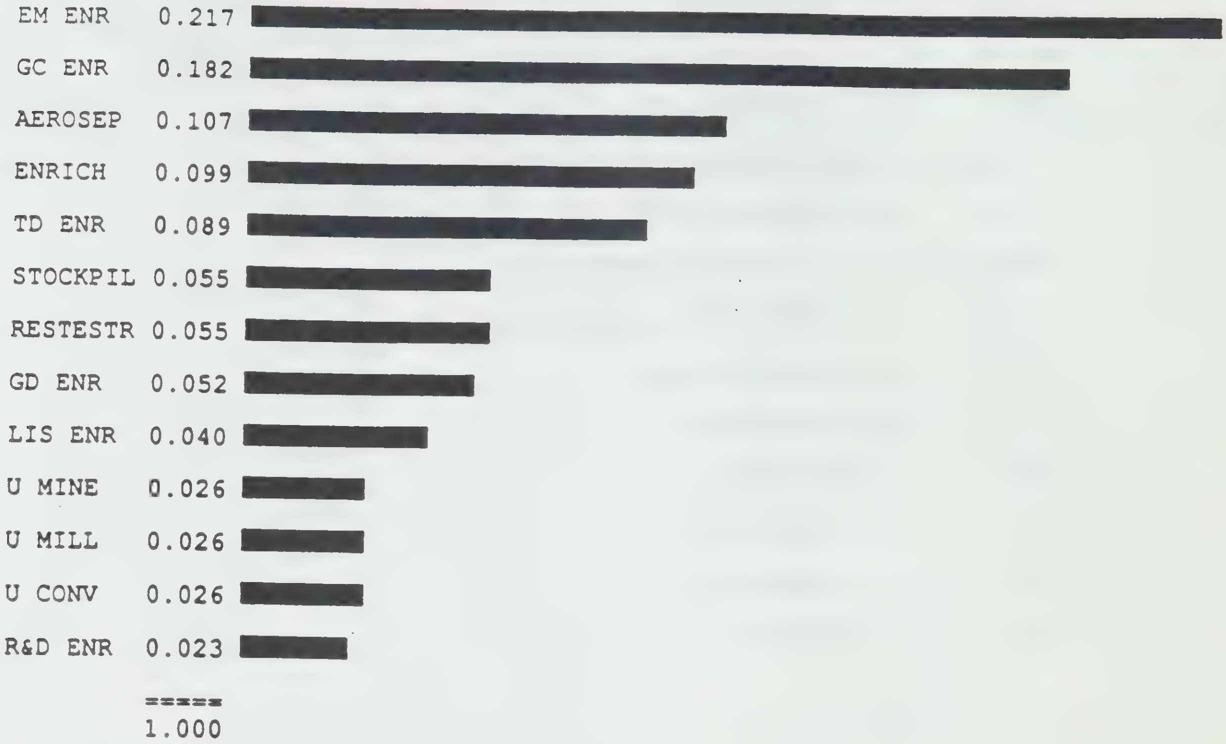
Figure 2.1.1b
Risk Ranking (U-235 Diversion) for Declared Facilities of a NNWSD

C:\EC\FIG211C 05-15-1994 AECL Research

RISK RANKING NNWSU U-235 FOR DECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.08



AEROSEP --- AERODYNAMIC HELIKON SEPARATION TECHNIQUE
EM ENR --- ELECTROMAGNETIC ENRICHMENT
ENRICH --- ENRICHED U CONVERSION FACILITY/FUEL FABRICATION FACILITY
GC ENR --- HIGH SPEED GAS CENTRIFUGE ENRICHMENT
GD ENR --- GASEOUS DIFFUSION ENRICHMENT
LIS ENR --- LASER ISOTOPE ENRICHMENT
R&D ENR --- ENRICHMENT TECHNIQUES AT R & D STAGE
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- ENRICHED U-235 MATERIAL AVAILABLE FROM STOCKPILES
TD ENR --- THERMAL DIFFUSION ENRICHMENT
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL
U MINE --- URANIUM MINE

Figure 2.1.1c
Risk Ranking (U-235 Diversion) for Declared Facilities of a NNWSU

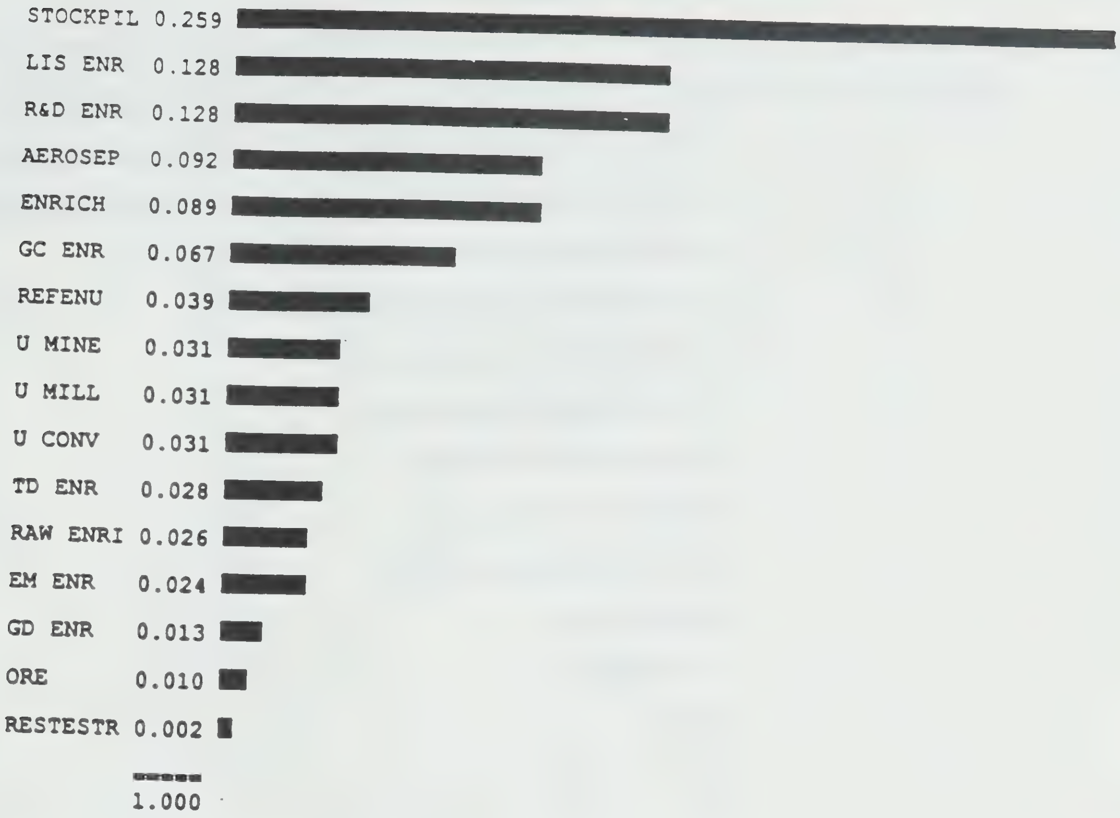
C:\EC\FIG221A 05-10-1994

AECL Research

RISK RANKING NWS U-235 FOR UNDECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.13



AEROSEP --- AERODYNAMIC HELIKON SEPARATION TECHNIQUE
EM ENR --- ELECTROMAGNETIC ENRICHMENT
ENRICH --- CONVERSION FACILITY/FUEL FABRICATION FACILITY FOR HEU
GC ENR --- HIGH SPEED GAS CENTRIFUGE ENRICHMENT
GD ENR --- GASEOUS DIFFUSION ENRICHMENT
LIS ENR --- LASER ISOTOPE SEPARATION ENRICHMENT
ORE --- SMUGGLED NATURAL ORE
R&D ENR --- ENRICHMENT TECHNIQUES AT R & D STAGE
RAW ENRI --- SMUGGLED RAW ENRICHED URANIUM
REFENU --- SMUGGLED REFINED ENRICHED URANIUM
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- ENRICHED MATERIAL AVAILABLE FROM STOCKPILES
TD ENR --- THERMAL DIFFUSION ENRICHMENT
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL

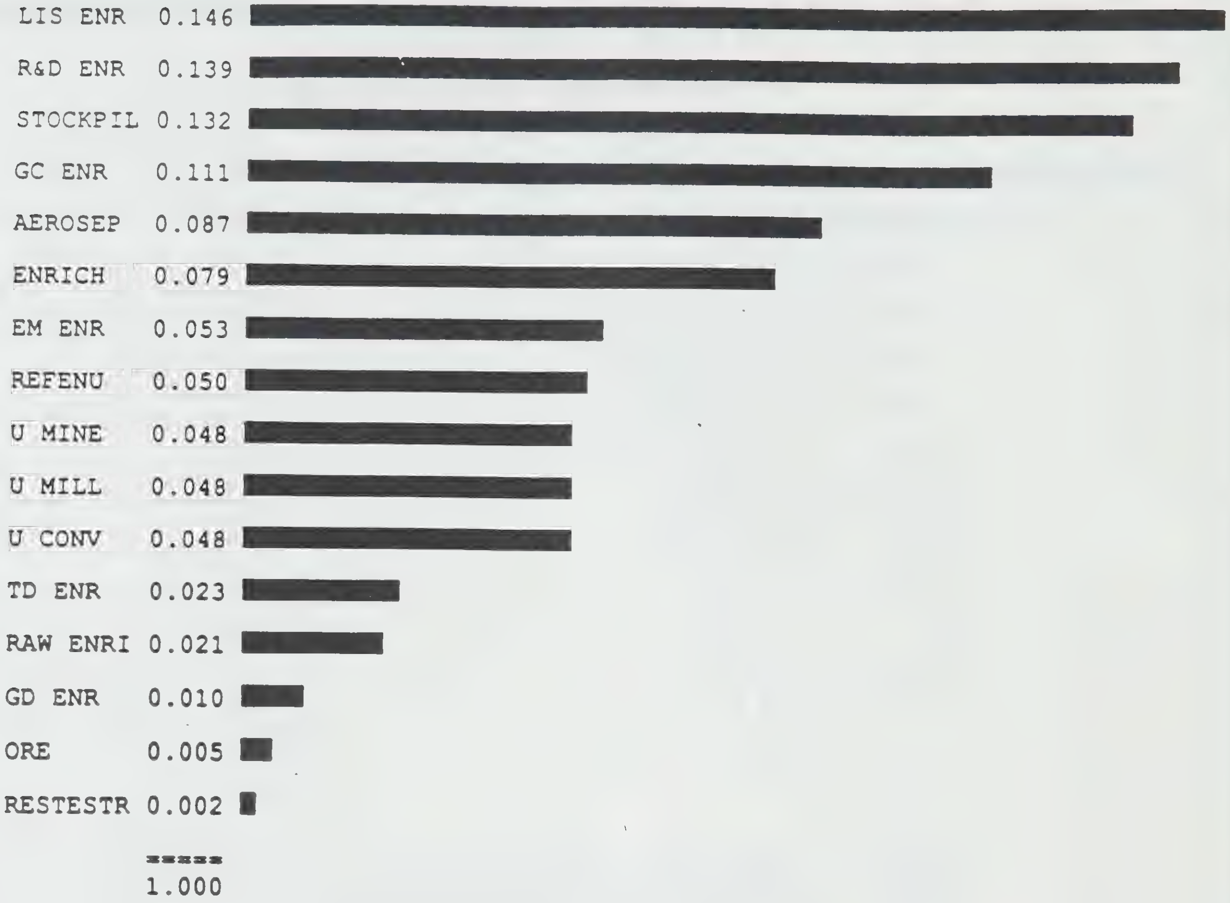
Figure 2.2.1a
Risk Ranking ((U-235 Diversion) for Undeclared Facilities of a NWS

C:\EC\FIG221B 05-10-1994 AECL Research

RISK RANKING NNWSD U-235 FOR UNDECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.08



AEROSEP --- AERODYNAMIC HELIKON SEPARATION TECHNIQUE
EM ENR --- ELECTROMAGNETIC ENRICHMENT
ENRICH --- CONVERSION FACILITY FOR ENRICHED URANIUM
GC ENR --- HIGH SPEED GAS CENTRIFUGE ENRICHMENT
GD ENR --- GASEOUS DIFFUSION ENRICHMENT
LIS ENR --- LASER ISOTOPE SEPARATION ENRICHMENT
ORE --- SMUGGLED NATURAL ORE
R&D ENR --- ENRICHMENT TECHNIQUES AT R & D STAGE
RAW ENRI --- SMUGGLED RAW ENRICHED URANIUM
REFENU --- SMUGGLED REFINED ENRICHED URANIUM
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- ENRICHED MATERIAL AVAILABLE FROM STOCKPILES
TD ENR --- THERMAL DIFFUSION ENRICHMENT
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL

Figure 2.2.1b
Risk Ranking (U-235 Diversion) for Undeclared Facilities of a NNWSD

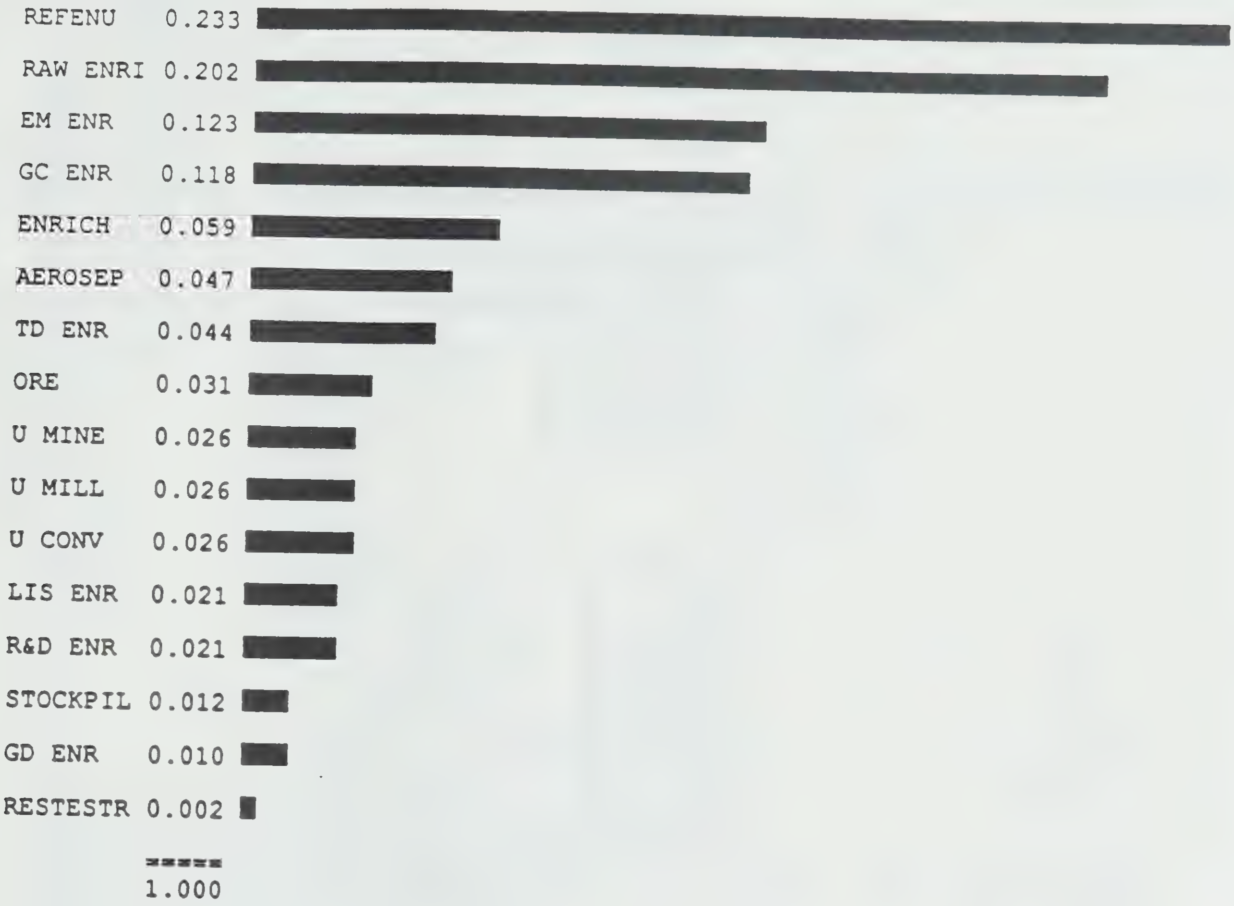
C:\EC\FIG221C 05-10-1994

AECL Research

RISK RANKING NNWSU U-235 FOR UNDECLARED FACILITIES

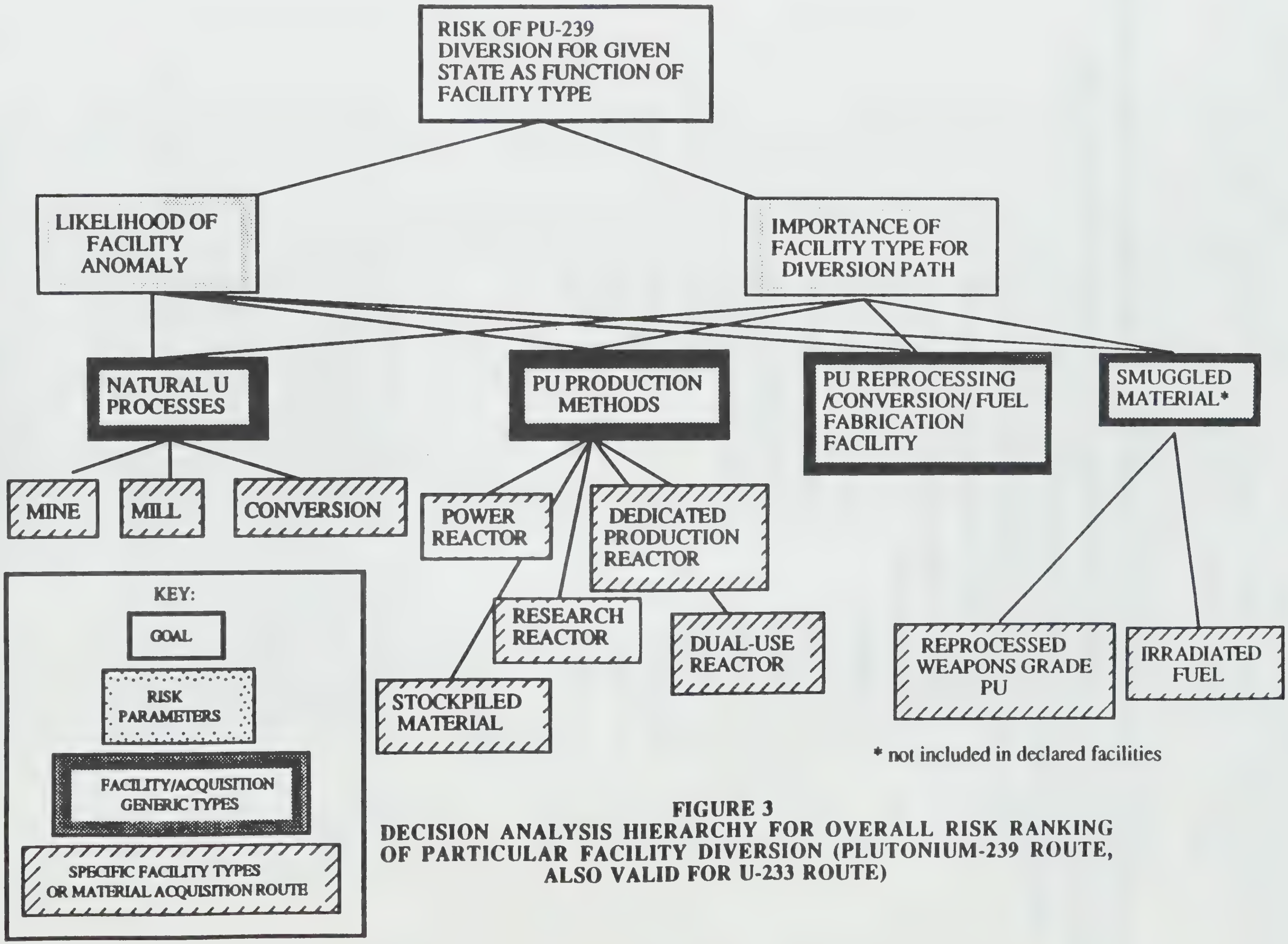
Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.06



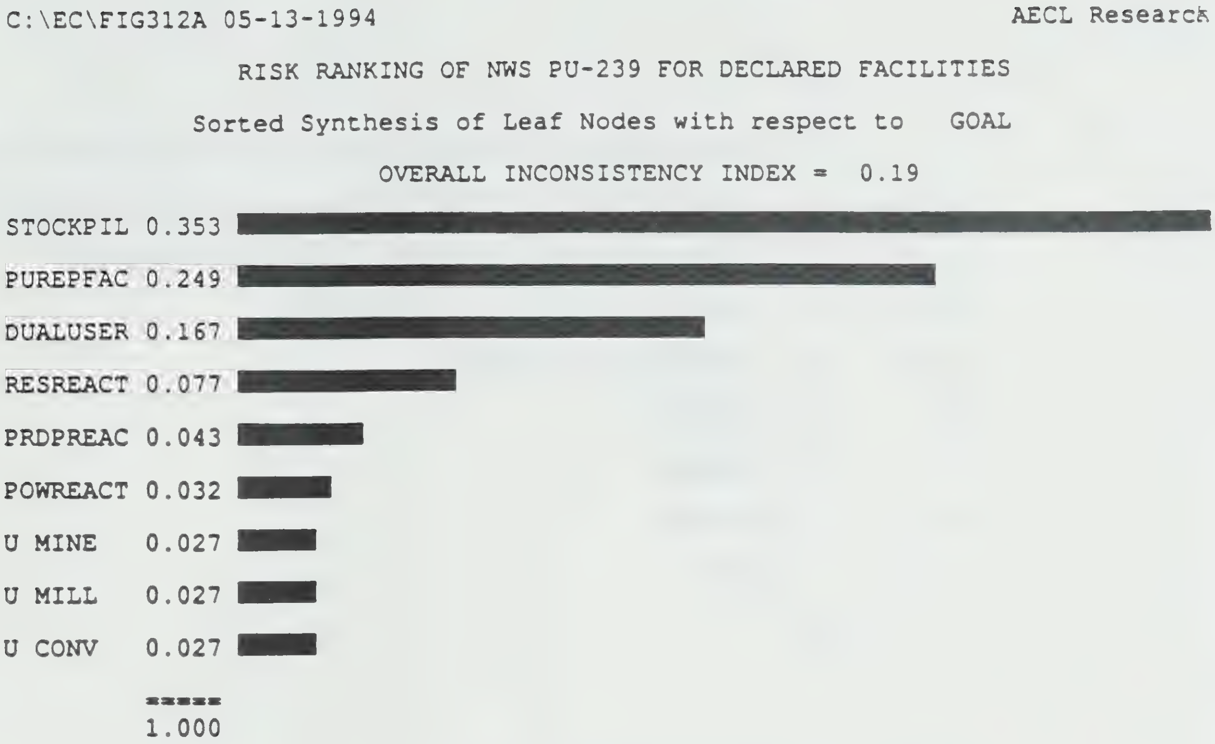
AEROSEP --- AERODYNAMIC HELIKON SEPARATION TECHNIQUE
EM ENR --- ELECTROMAGNETIC ENRICHMENT
ENRICH --- CONVERSION FACILITY FOR ENRICHED URANIUM
GC ENR --- HIGH SPEED GAS CENTRIFUGE ENRICHMENT
GD ENR --- GASEOUS DIFFUSION ENRICHMENT
LIS ENR --- LASER ISOTOPE SEPARTION ENRICHMENT
ORE --- SMUGGLED NATURAL ORE
R&D ENR --- ENRICHMENT TECHNIQUES AT R & D STAGE
RAW ENRI --- SMUGGLED RAW ENRICHED URANIUM
REFENU --- SMUGGLED REFINED ENRICHED URANIUM
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- ENRICHED U-235 MATERIAL AVAILABLE FROM STOCKPILES
TD ENR --- THERMAL DIFFUSION ENRICHMENT
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL

Figure 2.2.1c
Risk Ranking (U-235 Diversion) for Undeclared Facilities of a NNWSU



* not included in declared facilities

FIGURE 3
DECISION ANALYSIS HIERARCHY FOR OVERALL RISK RANKING OF PARTICULAR FACILITY DIVERSION (PLUTONIUM-239 ROUTE, ALSO VALID FOR U-233 ROUTE)



DUALUSER --- DUAL USE REACTOR
POWREACT --- CIVILIAN POWER REACTORS
PRDPREAC --- MILITARY PRODUCTION REACTORS
PUREPFAC --- PLUTONIUM REPROCESSING/CONVERSION/FUEL FABRICATION FACILITY
RESREACT --- RESEARCH/TEST REACTOR
STOCKPIL --- PLUTONIUM STOCKPILES
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL
U MINE --- URANIUM MINE

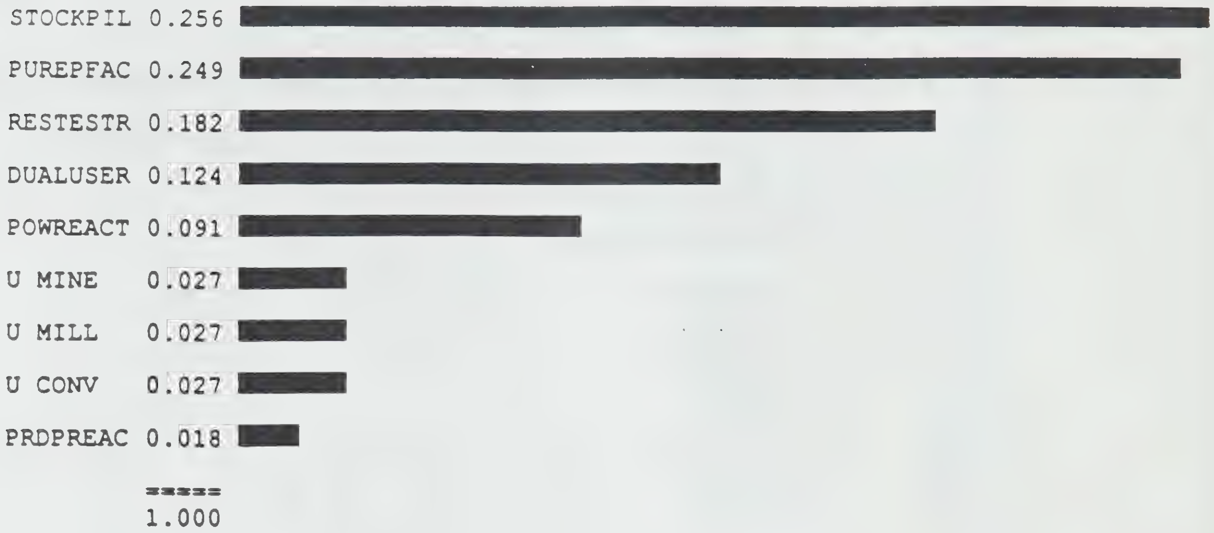
Figure 3.1.2a
Risk Ranking (Pu-239 Diversion) for Declared Facilities of a NWS

C:\EC\FIG312B 07-24-1994 AECL Research

RISK RANKING OF NNWSD PU-239 FOR DECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.17



DUALUSER --- DUAL USE REACTOR
POWREACT --- CIVILIAN POWER REACTORS
PRDPREAC --- MILITARY PRODUCTION REACTORS
PUREPFAC --- PLUTONIUM REPROCESSING/CONVERSION/FUEL FABRICATION FACILITY
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- PLUTONIUM STOCKPILES
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL
U MINE --- URANIUM MINE

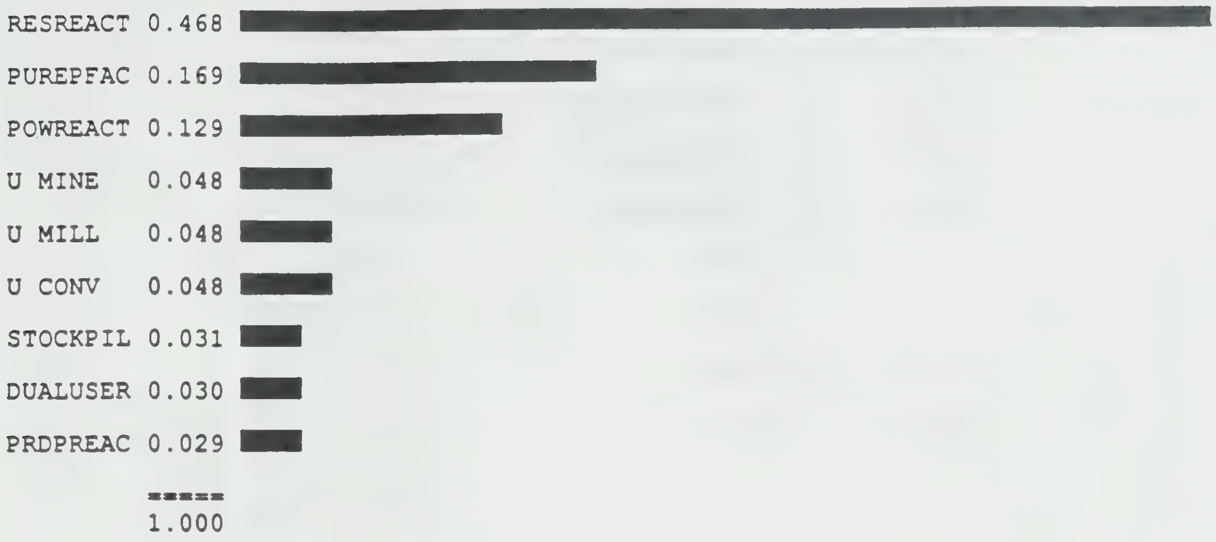
Figure 3.1.2b
Risk Ranking (Pu-239 Diversion) for Declared Facilities of a NNWSD

C:\EC\FIG312C 05-13-1994 AECL Research

RISK RANKING OF NNWSU PU-239 FOR DECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.16



DUALUSER --- DUAL USE REACTOR
POWREACT --- CIVILIAN POWER REACTORS
PRDPREAC --- MILITARY PRODUCTION REACTORS
PUREPFAC --- PLUTONIUM REPROCESSING/CONVERVERSION/FUEL FABRICATION FACILITY
RESREACT --- RESEARCH/TEST REACTOR
STOCKPIL --- PLUTONIUM STOCKPILES
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL
U MINE --- URANIUM MINE

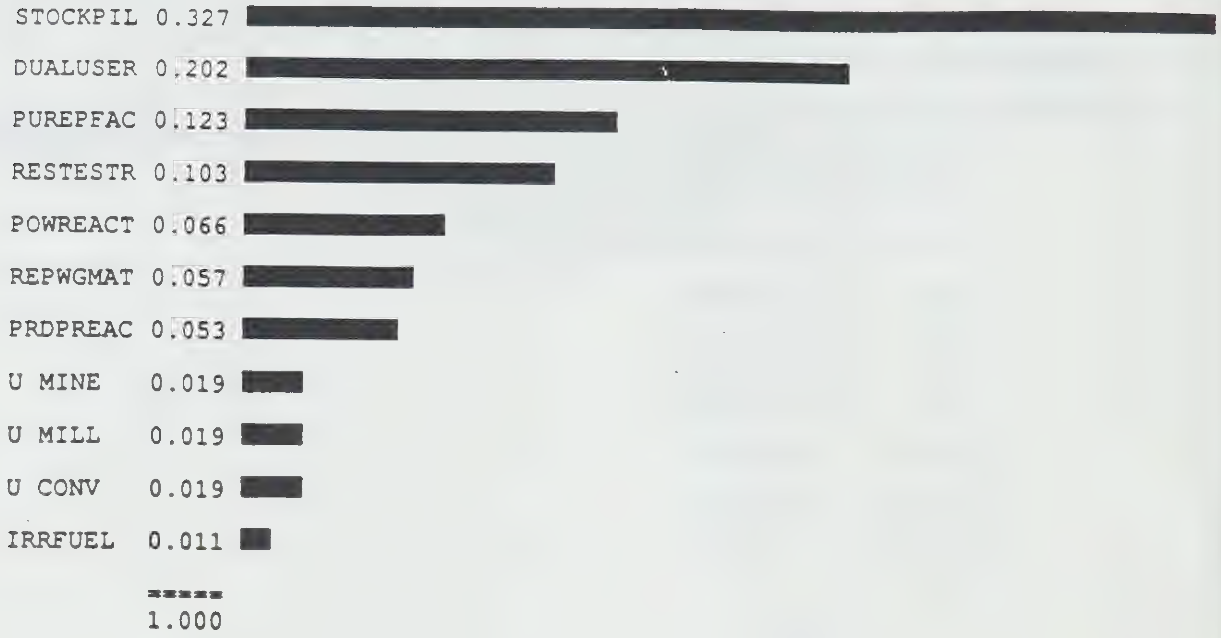
Figure 3.1.2c
Risk Ranking (Pu-239 Diversion) for Declared Facilities of a NNWSU

C:\EC\FIG322A 07-24-1994 AECL Research

RISK RANKING OF NWS PU-239 FOR UNDECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.09



DUALUSER	---	DUAL USE REACTOR
IRRFUEL	---	SMUGGLED IRRADIATED FUEL
POWREACT	---	CIVILIAN POWER REACTORS
PRDPREAC	---	MILITARY PRODUCTION REACTORS
PUREPFAC	---	PLUTONIUM REPROCESSING/CONVERVERSION/FUEL FABRICATION FACILITY
REPWGMAT	---	REPROCESSED WEAPON GRADE MATERIAL SMUGGLED SOURCE
RESTESTR	---	RESEARCH/TEST REACTORS
STOCKPIL	---	PLUTONIUM STOCKPILES
U CONV	---	NATURAL URANIUM CONVERSION
U MILL	---	URANIUM MILL
U MINE	---	URANIUM MINE

Figure 3.2.2a
Risk Ranking (Pu-239 Diversion) for Undeclared Facilities of a NWS

C:\EC\FIG322B 07-24-1994 AECL Research

RISK RANKING OF NNWSD PU-239 FOR UNDECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.10


```
DUALUSER --- DUAL USE REACTOR
IRRFUEL  --- SMUGGLED IRRADIATED FUEL
POWREACT --- CIVILIAN POWER REACTORS
PRDPREAC --- MILITARY PRODUCTION REACTORS
PUREPFAC --- PLUTONIUM REPROCESSING/CONVERVERSION/FUEL FABRICATION FACILITY
REPWGMAT --- REPROCESSED WEAPON GRADE MATERIAL SMUGGLED SOURCE
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- PLUTONIUM STOCKPILES
U CONV   --- NATURAL URANIUM CONVERSION
U MILL   --- URANIUM MILL
U MINE   --- URANIUM MINE
```

Figure 3.2.2b
Risk Ranking (Pu-239 Diversion) for Undeclared Facilities of a NNWSD

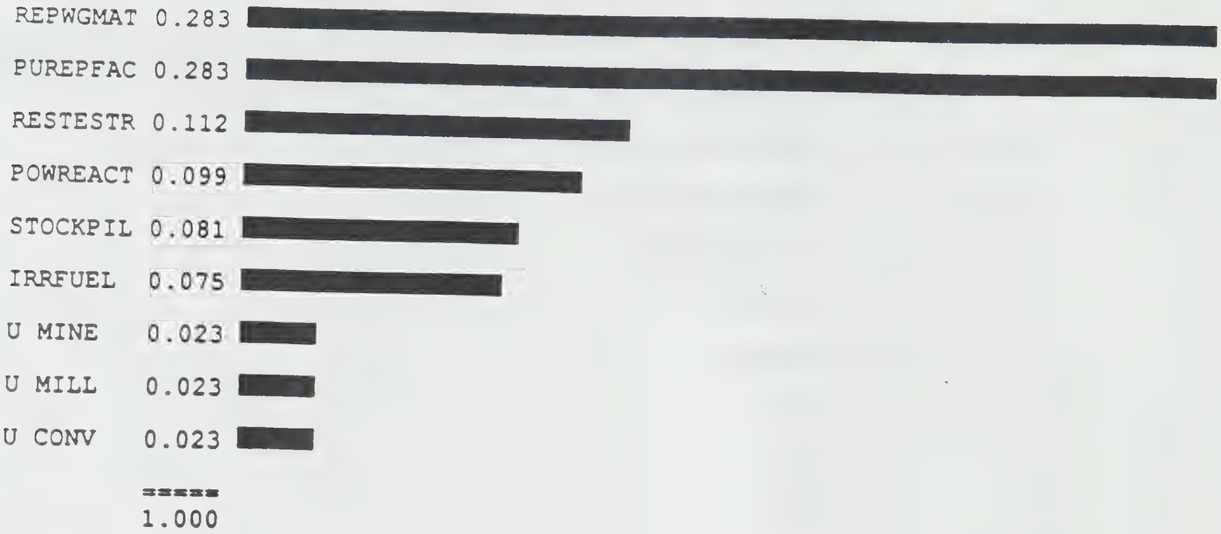
C:\EC\FIG322C 07-25-1994

AECL Research

RISK RANKING OF NNWSU PU-239 FOR UNDECLARED FACILITIES

Sorted Synthesis of Leaf Nodes with respect to GOAL

OVERALL INCONSISTENCY INDEX = 0.08



IRRFUEL --- SMUGGLED IRRADIATED FUEL
POWREACT --- CIVILIAN POWER REACTORS
PUREPFAC --- PLUTONIUM REPROCESSING/CONVERVERSION/FUEL FABRICATION FACILITY
REPWGMAT --- REPROCESSED WEAPON GRADE MATERIAL SMUGGLED SOURCE
RESTESTR --- RESEARCH/TEST REACTORS
STOCKPIL --- PLUTONIUM STOCKPILES
U CONV --- NATURAL URANIUM CONVERSION
U MILL --- URANIUM MILL
U MINE --- URANIUM MINE

Figure 3.2.2c
Risk Ranking (Pu-239 Diversion) for Undeclared Facilities of a NNWSU

Appendix A

Fissile Material Cut-off Bibliography List

As the cut-off literature by its nature becomes outdated over time, the bibliography is provided in reverse chronological order, with recent references first, for convenience. References providing specific technical information on nuclear weapons materials have been provided in a separate listing below. The most relevant items have been noted with a vertical bar paragraph marker; with brief summaries of some of these being provided in Appendix B.

1. McFate, P.B., Greybeal, S.N., Lindsey,G., Kilgour, D. M. CONSTRAINING PROLIFERATION: THE CONTRIBUTION OF VERIFICATION SYNERGIES. Arms Control Verification Studies No. 5. Ottawa: Department of External Affairs, Non-Proliferation, Arms Control and Disarmament Division, March 1993.

2. Perkins, R.W., Wogman, N.A. CURRENT AND POTENTIAL TECHNOLOGIES FOR THE DETECTION OF RADIONUCLIDE SIGNATURES OF PROLIFERATION, (R & D EFFORTS), Pacific Northwest Lab., Richland, WA DOE, Washington, DC (United States), Department of Energy International Safeguard Meeting, 22-23 Mar. 1993.

3. Belew, W.L., Carter, J.A.,Smith, D.H., Walker, R.L. DETECTION OF URANIUM ENRICHMENT ACTIVITIES USING ENVIRONMENTAL MONITORING TECHNIQUES, Pacific Northwest Lab., Richland, WA, DOE, Washington, DC Department of Energy International Safeguards Meeting, 22-23 Mar. 1993.

4. Swahn, J. THE LONG-TERM NUCLEAR EXPLOSIVES PREDICAMENT: THE FINAL DISPOSAL OF MILITARILY USABLE FISSILE MATERIAL IN NUCLEAR WASTE FROM NUCLEAR POWER AND FROM THE ELIMINATION OF NUCLEAR WEAPONS. Goteborg: Chalmers University of Technology, 1992.

5. Barnaby, F. PLUTONIUM AND SECURITY, New York, NY, St. Martins Press, 1992.

6. Sharma, S.K. "Cut-off on Production of Fissionable Material for Weapons Purposes". In: VERIFICATION OF DISARMAMENT OR LIMITATION OF ARMAMENTS: INSTRUMENTS, NEGOTIATIONS, PROPOSALS. Edited by Serge Sur. Geneva: United Nations Institute for Disarmament Research, 1992.

7. Neuhoff, J., Singer, C. "The Verification and Control of Fissile Material in South Asia". In: NUCLEAR PROLIFERATION IN SOUTH ASIA: THE PROSPECTS FOR ARMS CONTROL. Edited by S. P. Cohen. New Delhi: Lancer International, 1991.

8. Federation of American Scientists. ENDING THE PRODUCTION OF FISSILE MATERIALS FOR WEAPONS: VERIFYING THE DISMANTLEMENT OF NUCLEAR WARHEADS. Washington, D.C., 1991.

9. Scheinmann, L., G\ rdzitel, I.G. "Verifying a Production Cut-off for Nuclear Explosive Material: Strategies for Verification and the Role of the IAEA". In: VERIFICATION: MONITORING DISARMAMENT. Edited by F. Calogero; M. L. Goldberger; S. P. Kapitza. Boulder, Colorado: Westview Press, 1991.

10. Nye, J.S. Jr., Graham, T.W., Smith, R. THE SPREAD OF NUCLEAR WEAPONS AND NUCLEAR TERRORISM, (Harvard's Center for Science and International Affairs (US)), Lanham, MD (USA) Univ. Press of America Inc., 1990.

11. Taylor, T. "Global Abolition of Nuclear Weapons - Verification of Compliance and Deterrents to Violation". Paper presented at 40th Pugwash Conference on Science and World Affairs, Egham, U.K., September 1990.

12. Thompson, G. "Verification of a Cut-Off in the Production of Fissile Material". In: A HANDBOOK OF VERIFICATION PROCEDURES. Edited by F. Barnaby. Basingstoke: MacMillan, 1990.

13. Donnelly, W.H.; Scheinmann, L. NEW CONCEPTS IN NUCLEAR ARMS CONTROL: VERIFIED CUT-OFF AND VERIFIED DISPOSAL. Occasional Paper No. 5. Southampton, UK: Programme for Promoting Nuclear Non-Proliferation, Centre for International Policy Studies, University of Southampton, 1990.

14. Gverdziteli, I.G. "Verifying a Production Cut-off for Nuclear Explosive Material: IAEA Safeguards Against Diversion and Proliferation". In: VERIFICATION: MONITORING ARMS CONTROL. Edited by S. Kapitza; J. Goldberger; J. Holdren. Boulder, Colorado: Westview Press, 1990.

15. Von Hippel, F. "Warhead and Fissile-Material Declarations". In: REVERSING THE ARMS RACE: HOW TO ACHIEVE AND VERIFY DEEP REDUCTIONS IN THE NUCLEAR ARSENALS. Edited by F. von Hippel; R. Z. Sagdeev. New York: Gordon and Breach Science Publishers, 1990.

16. Rodionov, S.N. "Verification of Compliance and Deterrents to Violations: Comments on the Paper by Theodore Taylor". Paper presented at 40th Pugwash Conference on Science and World Affairs, Egham, U.K., September 1990.

17. Donnelly, W. H. PROPOSALS FOR ENDING U.S. AND SOVIET PRODUCTION OF FISSILE MATERIALS FOR NUCLEAR WEAPONS. Washington, D.C.: Congressional Research Service, Library of Congress, 3 April 1990.

18. Lecocq, A. "Disposal of Fissile Material from Nuclear Weapons". In: VERIFICATION OF ARMS REDUCTIONS: NUCLEAR, CONVENTIONAL AND CHEMICAL. Edited by J. Altmann; J. Rotblat. New York: Springer Verlag, 1989.

19. Lanouette, W., PLUTONIUM - NO SUPPLY NO DEMAND, The Bulletin of Atomic Scientists, December 1989, p.42.

20. Pinchukov, Y. "Cessation of Fissionable Material Production and Elimination of Nuclear Weapons". In: DISARMAMENT AND SECURITY: IMEMO YEARBOOK 1988-1989. Moscow: Novosti Press Agency Publishing House, 1989.

21. Scheinmann, L. VERIFICATION OF A FISSILE MATERIAL PRODUCTION CUT-OFF. U.S. Pugwash/Soviet Academy of Science Study, 1989.

22. Carson, M. J., THE TRITIUM FACTOR AS A FORCING FUNCTION IN NUCLEAR ARMS REDUCTION TALKS, Science, Volume 241, p. 1166, September 1988.

23. Ellis, M. THE VERIFICATION ISSUE IN UNITED NATIONS DISARMAMENT NEGOTIATIONS. Geneva: United Nations Institute for Disarmament Research, 1987.

24. Von Hippel, F. "Verification of a Cut-off in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons". In: PROCEEDINGS OF THE WORKSHOP: SCIENTIFIC ASPECTS OF THE VERIFICATION OF ARMS CONTROL TREATIES. Edited by Hartwig Spitzer. Vol. 19. Hamburg: Universitat Hamburg, Institut fur Friedensforschung und Sicherheitspolitik, June 1987.

25. Levi, B., von Hippel, F. "Verifiability of a Cut-Off of the Production of Fissile Material for Nuclear Weapons". In: VERIFYING A NUCLEAR FREEZE. Edited by R. Harrison. New Hampshire: Berg Publishers Ltd., 1986.

26. Von Hippel, F., Levi, B.G. "Controlling Nuclear Weapons at the Source: Verification of a Cut-off in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons". In: ARMS CONTROL VERIFICATION: THE TECHNOLOGIES THAT MAKE IT POSSIBLE. Edited by K. Tsipis; D. W. Hafemeister; P. Janeway. Toronto: Pergamon-Brassey's International Defense Publishers, 1986.

27. Weinstock, E.V., Fainberg, A. "Verifying a Fissile-Material Production Freeze in Declared Facilities, with Special Emphasis on Remote Monitoring". In: ARMS CONTROL VERIFICATION: THE TECHNOLOGIES THAT MAKE IT POSSIBLE. Edited by K. Tsipis; D. W. Hafemeister; P. Janeway. Toronto: Pergamon-Brasey's International Defense Publishers, 1986.

28. Von Hippel F., Albright, D., Levi, B.G. "Stopping the Production of Fissile Materials for Weapons". SCIENTIFIC AMERICAN. Vol. 253, No. 3, September, 1985.

29. Scoville, H. "First Steps Toward a Freeze". In: THE NUCLEAR WEAPONS FREEZE AND ARMS CONTROL. Edited by S.E. Miller. Cambridge, Mass.: Ballinger, 1984.

30. Sharp, J.M.O. "Exploring the Feasibility of a Ban on Warhead Production". In: THE NUCLEAR WEAPONS FREEZE AND ARMS CONTROL. Edited by Steven E. Miller. Cambridge, Mass.: Ballinger, 1984.

31. Stoertz, Jr., H., "Monitoring a Nuclear Freeze". INTERNATIONAL SECURITY. Vol. 8, No. 4, 1984.

32. Krass A.S., Boskma P., Elzen B. and Smit W.A., URANIUM ENRICHMENT AND NUCLEAR WEAPON PROLIFERATION, International Publications Service, Taylor & Francis Inc., New York, 1983.

33. Gayler, N. "A Proposal for Deep Cuts". BULLETIN OF THE ATOMIC SCIENTISTS. Vol. 39, December 1983.

34. Federation of American Scientists. "Verifying a Model Freeze". CONGRESSIONAL RECORD. 14 April 1983.

35. Stares, P. "Can a Nuclear Freeze be Verified". In: THE NUCLEAR FREEZE DEBATE: ARMS CONTROL ISSUES FOR THE 1980s. Edited by Paul M. Cole; William J. Taylor. Boulder, Colorado: Westview Press, 1983.

36. Niedergang, M. "Verification of a Nuclear Weapons Freeze". BULLETIN OF PEACE PROPOSALS. Vol. 13, No. 3, 1982.

37. Fischer, D. "Safeguards - A model for General Arms Control?". IAEA BULLETIN. Vol. 24, No. 2, June 1982.

38. Epstein, W. "A Ban on the Production of Fissionable Material for Weapons". SCIENTIFIC AMERICAN. Vol. 243, No. 1, July 1980.

39. United Kingdom, THE TECHNICAL POSSIBILITY OF INTERNATIONAL CONTROL OF FISSILE MATERIAL PRODUCTION. ENDC/60. 31 August 1972.

40. United States. WORKING PAPER ON TRANSFER OF FISSIONABLE MATERIAL OBTAINED BY THE DESTRUCTION OF NUCLEAR WEAPONS. ENDC/172. 8 March 1966.

41. United States. WORKING PAPER ON AN INSPECTION METHOD FOR VERIFYING THE STATUS OF SHUTDOWN PLUTONIUM PRODUCTION REACTORS. ENDC/174. 14 APRIL 1966.

42. United States. WORKING PAPER ON INSPECTION OF A FISSIONABLE MATERIAL CUT-OFF. ENDC/134. 25 June 1964.

43. Penrose, L.S. "Radiation, Public Health and Inspection for Disarmament". In: INSPECTION FOR DISARMAMENT. Edited by Seymour Melman. New York: Columbia University Press, 1958.

44. Fox, M.C., THERMAL DIFFUSION AS ADJUNCT OF THE ELECTROMAGNETIC PROCESS, Chemical and Metallurgical Engineering, December 1945, p.102.

Nuclear Weapon Material; Unclassified Technical Information References

i. National Academy of Sciences, MANAGEMENT AND DISPOSITION OF EXCESS WEAPONS OF PLUTONIUM, National Academy Press, Washington, DC, 1994.

ii. Seaborg G.T., Loveland, W.D., THE ELEMENTS BEYOND URANIUM. New York, Wiley, 1990 (p.309, "Nuclear Weapons").

iii. Fetter, S., Frolov, V.A., Prilutsky, O.F., Sagdeev, R. Z., Fissile Materials and Weapon Models, Appendix 11.A, REVERSING THE ARMS RACE, von Hippel, 1990, Bibiography Reference #15.

iv. Taylor, T. NUCLEAR SAFEGUARDS, Annual Review of Nuclear Science, Vol.25, p.407, 1975, Annual Reviews Inc.

v. Wilkie T., OLD AGE CAN KILL THE BOMB, New Scientist, 16 February 1984, p.27.

vi Hoddeson, L., Henriksen, P., Meade, M., Westfall, C., CRITICAL ASSEMBLY, Cambridge University Press, 1993.

Appendix B

Summary Review of Selected Cut-off Article References 1980-1993

1980: **Epstein W. "A Ban on the Production of Fissionable Material from Weapons", Scientific American, Vol.243, p.43.**

Epstein discusses the benefit of banning the production of fissionable material for nuclear weapons, in addition to the prospects of a CTB under discussion at this time of writing. Cut-off of NWS as well as prohibition in NNWS is implied. Proposal was intended to halt vertical spread of numbers of weapons (at that time, increase in the number of and the type of nuclear weapons in the NWS) and the horizontal spread spread of nuclear weapons to NNWS. An additional reason for cut-off identifies the HEU weapon stockpile. This could provide a source of LEU for power reactors and postpone the need for commercial breeder reactors and the plutonium economy. The reduction of weapons proliferation, likely with breeders and Pu recycling is also identified. The article provides a brief historical review of cut-off with various proposals being linked to the political changes in the period from 1946 to 1979. The latter is extensive and informative. Little discussion is provided on verification issues, or on the specific types of facilities involved.

1983 **Krass A.S., Boskma P., Elzen B. and Smit W. A., "Uranium Enrichment and Nuclear Proliferation", International Publications Service, Taylor & Francis Inc., New York.**

Although now somewhat dated, this book provides an excellent review of the state of the art of uranium enrichment techniques existing at that time, which should be easily understood by the non-technical specialist. A qualitative risk ranking of proliferation, using the U-235 route, of the various enrichment techniques is provided. The risk ranking is based on technical features of the techniques for an overall generic-risk basis and also a state-specific-risk basis, based on the known technology status at that time. The technical methods are also placed in the context of the economic and institutional environment within which the enrichment industry has evolved. Measures which might be taken to reduce the proliferation risk from the industry are discussed.

1986: **von Hippel F., Levi B.G. "Controlling Nuclear Weapons at the Source: Verification of a Cut-off in the Production of Plutonium and Highly Enriched Uranium for Nuclear Weapons", Arms Control Verification, Pergamon-Brassey's.**

A very clearly written and extensive review article containing much of the of the material on the same subject published by von Hippel in other articles around this time [Bib. articles 24, 25, and 28]. The article addresses cut-off history very briefly. A discussion is provided of the status of U-235 and Pu-239 production and estimated US stockpiles at the time of writing and of verification aspects of a cut-off of the production of fissionable material, with specific regard to the potential role of the IAEA. Verification for specific declared production facilities is discussed.

1986 Weinstoc E.V., Fainberg, A. "Verifying a Fiss Material Produ tion Freeze in Declared Facilities, with Special Emphasis on Remote Monitoring". Arms Control Verification, Pergamon-Brassey's.

The article is in the same book as, and complements, the previous reference. Descriptions of the technology for monitoring nuclear materials in declared civilian facilities are provided and the methods and equipment available for monitoring a materials cut-off are clearly described. An excellent overview is given of the problems and available solutions in the international effort to restrict the production of nuclear materials.

1993 Perkins, R.W., Wogman, N.A. "Current and Potential Technologies for the Detection of Radionuclide Signatures of Proliferation (R & D Efforts)", Pacific Northwest Lab., Department of Energy International Safeguard Meeting.

The many potential nuclear signatures of weapon fissile material are identified. The potential diversion paths discussed are fuel fabrication, uranium enrichment, reactor operation for plutonium production, fuel reprocessing for plutonium extraction, weapons fabrication and U-233 production. The most definitive signatures and appropriate environmental sampling and analysis techniques for observing the nuclear signatures are discussed, with the focus on technologies for the detection of diversion signatures that are in the concept or research and development stage.

Appendix C

Historical Review of Cut-Off and Related Proposals

1946

The US presented the Baruch Plan out of the Lilienthal Report, Washington, to the UN, following Hiroshima and Nagasaki, which proposed the complete international managerial control of the production of fissionable material. The plan was rejected by the USSR, following the Lilienthal report and the Washington declaration issued in 1945 by President Truman, Prime Minister Atlee and Prime Minister McKenzie King.

1953

Cut-off of fissionable material for weapons purposes for the NWS was proposed by the US (President Eisenhower) in the Atoms for Peace Conference of the UN in 1953. This proposal arose from the failure of the 1946 Baruch plan.

The proposal called for a production cut-off of weapons material and for contributions from stockpiles of natural uranium and fissionable material to a new international agency, empowered to promote and regulate the use of atomic energy for peaceful purposes. The object was to limit the amount of fissionable material available and hence limit the number of weapons.

1956

The US Secretary of State, Dulles, on behalf of the US, Canada, France and the UK proposed to the five-member UN Disarmament Commission that all future production of fissionable material be used under international supervision exclusively for non-weapons purposes. The USSR rejected the proposal on the basis that banning weapon-fissile material without also banning weapons was impractical.

1957

The IAEA is formed, leading from the part of Eisenhower's 1953 proposal that was to promote and regulate the peaceful use of atomic energy.

Implementation of safeguards activities was initiated by the trilateral agreements between the IAEA supplier state and recipient state. The agency was delegated supplier's right of safeguarding nuclear materials under the INFCIRC 66 system.

The UN adopted, over USSR opposition, a resolution giving priority to a number of disarmament measures, which included the cessation of production of fissionable material for weapons purposes. This was the first time the General Assembly had adopted a resolution dealing with cut-off.

1964

US President Johnson proposed to the United Nations Conference on Disarmament an agreement for a cut-off starting with verified plant-by-plant shutdowns.

The same year, the US stated that it would cease production of U-235 for weapons purposes, due to the fact that the U-235 stockpile far exceeded requirements for weapons using this material. Pu-239 production was also decreased. The USSR and the UK separately announced reductions in the production rates of fissionable material.

The US then submitted a working paper in support of a complete cut-off, outlining non-intrusive verification procedures and proposing the conversion of weapons material for peaceful purposes. The USSR doubted that a separate agreement on cut-off was possible without a general disarmament agreement.

1966

In three working papers the US proposed the transfer of fissionable material from weapons, and the provision of inspection procedures for production facilities.

1969

US President Nixon presented cut-off as an item in the Geneva Conference on Disarmament meetings. The NWS were to accept the same IAEA safeguards required for the NNWS under the NPT. The USSR did not agree with the proposals. The issue of cut-off was not high on agendas until the UN Special Session on Disarmament (UNSSD) 10 years later.

1978

At the UNSSD in May/June 1978 several countries supported cut-off. Canadian Prime Minister Trudeau, in particular, included cut-off as part of a "strategy of suffocation" concerning nuclear weapons. The final document called for the cessation of the production of nuclear weapons as well as fissionable materials for weapons purposes.

At a later regular session of the general assembly, Canada proposed a cut-off resolution for a cessation of current fissionable material production and new production, and included a ban on "peaceful" nuclear explosions. The USSR and Eastern bloc opposed the resolution as not going far enough to stop weapons production. The resolution was adopted by a majority vote. Various cut-off resolutions were then regular features of the UNGA since this time.

1980

The US agreed to put some civilian nuclear facilities under IAEA safeguards.

1982

President Gromyko announced that the USSR was willing to put some civilian nuclear installations under IAEA safeguards.

1993

A UNGA consensus resolution called for a non-discriminatory, multilateral and verifiable treaty banning production of fissile material for nuclear weapons and nuclear explosive devices. The resolution requested that the IAEA provide assistance in the verification arrangements for such a treaty.

Appendix D

Application of Decision Analysis Software, Expert Choice™, for Ranking Subjective Variables

D.1 Introduction to Expert Choice™

The well-recognized decision analysis software, "Expert Choice™" [D1], based on the analytic hierarchy process (AHP) formulated by Saaty [D2], is used to provide a method for ranking the relative likelihood of facility anomaly, according to the three types of states defined. The method consists of an inverted, tree-like structure, in the form of hierarchies (or levels) of main categories and sub-categories. Figure D1 indicates, on the left-hand side, the terminology used in the report and, on the right-hand side, the general terminology used in Expert Choice. The hierarchy structure is produced by relating a single top requirement, for example, the Likelihood of a Facility Anomaly (for a given type of facility), to lower levels of criteria/factors. The level of detail increases as the hierarchy level increases. The highest hierarchy level, physically the lowest on the diagrammatic structure, represents the three state types for which the relative anomaly likelihood comparison is required. Figure 1 provides the basic hierarchy used for the likelihood parameter assessment. This particular hierarchy is generic for all facilities in the undeclared category and is used as an example, assuming a high-speed gas centrifuge facility. At each hierarchy level, the grouped variables (connected by lines) are compared qualitatively in a pairwise way. This type of pairwise comparison forms the basis of the technique and enables weightings of the variables in the different hierarchy levels to be established.

The reason for grouping each hierarchy level into different categories and sub-categories is that comparing large number of items all at the same level would be cumbersome, because of the large number and also because of the potential lack of any form of commonality between every item. The pairwise comparison method is more efficient, requiring fewer judgments, when the items are grouped.

D.2 Advantages of Use

With respect to the rationale of the choice of method, a number of different decision making methods were reviewed that potentially could be used when subjective, uncertain and widely disparate parameters have to be compared and quantified. The conclusions are summarized below.

The often-used normalization type of method has fundamental analytical problems, discussed by Saaty [D3], and should be avoided. Because the scales of measurement of the different criteria are not the same, there is then no way to make the answer meaningful, unless somehow the scales can be interpreted in terms of a single scale so that they can be combined in a final meaningful way.

The Delphi-type decision-modeling approach of Saaty [D2, P.69], has each member of an expert group responding anonymously to a previously prepared questionnaire. It still has the technical limitations of a normalization method of comparing simultaneously all the various variables. This avoids strong personality domination, but appears to create quite large uncertainties compared to a collegiate consensus type system, such as the AHP, so a Delphi approach is not favoured.

The Bayesian technique, which is a method of using data from generic sources as a surrogate to describe statistics for a similar but specific type of application for which little or no data exists, addresses the problem of absence of specific data in a technically rigorous manner, but does not provide any help when comparing different types of variables. In addition, the Bayesian technique is conceptually very difficult to understand and is complex mathematically, requiring distributions rather than single numbers to represent parameter values.

The AHP process therefore appears to offer the technically best method available for a decision analysis process that is required to handle the subjective comparisons of an analysis of this nature.

Its advantages, in terms of the software Expert Choice™, are:

- The analysis is mathematically not complex and could be manually approximately spot verified, independently of the software, if required, being linear additive manipulations with weighted model variables.
- The process can deal with the measurement of intangibles; political, social, ideological as well as economic and technical.
- The software is not very expensive (U.S. $500).
- Use of the basic options of the program can be learned in one or two days, with no prior experience. Changes, updates and sensitivity runs then can be made very quickly.
- The analytic hierarchy process is mathematically sound and simple for participants to input data, and is based primarily on the principle of pairwise parameter comparisons. The relative ranking scales chosen are soundly based upon psychological research, unlike the arbitrary scaling methods of a normalization method.

D.3 Example Use

D.3.1 Tree Structure and Terminology

A partially worked example is provided below to illustrate the method. Terminology as used in the program is used. Figure 1 represents the basic tree structure used. The tree branches down from the Goal (Likelihood of Facility Anomaly for an Undeclared Gas Centrifuge Facility), through to main and sub-category hierarchy levels, and finally down to the highest hierarchy level, the three types of states that are being compared.

The subjective variable pairwise comparisons used are those derived by the analyst based on expert opinion. The decision basis is highly visible and, with access to the program, changes for sensitivity purposes, updates or differing opinions, for example, can easily be made.

D.3.2 Ranking Process

Having built the model defining the ranking criteria for the states, the judgment process can be started.

First, the two main categories of Figure 1, in the second-level hierarchy, are compared with respect to their perceived relative importance to the goal. The qualitative pairwise assessments, numerically represented by a 0 to 10 scale, are qualitatively defined in Table D1. The actual judgments are documented in numerical matrix form in the Expert Choice files which provide an auditable decision basis. For example, it was judged that the SOCIO/ECONOMIC AND POLITICAL STATUS was MODERATELY MORE IMPORTANT than TECHNOLOGICAL CRITERIA RELEVANT TO AN UNDECLARED FACILITY. After assessing the main categories, the sub-categories are then similarly judged, each with respect their corresponding main categories. These comparisons are also all subjective in this example.

Comparisons at each other hierarchy level, including the state types, are then made, on a pairwise, usually subjective basis, relative to each other, with respect to the above connecting sub-category. The overall rankings of the states are then obtained from all the above subjective input data by using the program, for the last analysis stage.

TABLE D1: The Verbal and Numerical Judgment Scale Used in Decision Analysis

Numerical Scale	Verbal Scale	Explanation
1.0	Equal importance of both elements	Two elements contribute equally to the consequence.
3.0	Moderate importance of one element over another	Experience and judgment favor one element over the other.
5.0	Strong importance of one element over another	An element is strongly favored.
7.0	Very strong importance of one element over another	An element is very strongly favored.
9.0	Extreme importance of one element over another	An element is favoured by at least an order of magnitude.
2.0, 4.0 6.0, 8.0	Intermediate values between two adjacent judgments	Used for compromise between two judgments.
Increments of 1.0	Intermediate value	Used for finer graduation of judgment in increments of 0.1.

D.3.3 Number of Comparisons

If there are n items, below a given node, to be pairwise compared, then the number of individual pairwise judgments to be entered will be (n)(n - 1) / 2. For example, if there are item comparisons where n = 3, there will then be three judgments to enter.

D.3.4 Inconsistency

As well as providing rankings based on judgments, Expert Choice™ provides a measure of consistency. This measure is useful in identifying possible errors in expressing judgments, as well as actual inconsistencies in judgments. The method does not actually preclude inconsistencies in judgments. On the contrary, the judgments recognize that different opinions as well as inconsistencies may well exist. To measure inconsistency, an Inconsistency Ratio (IR) is calculated below the final rankings for the relevant criteria, for a given node. Complete consistency gives an IR =0. The larger that IR is, the larger is the inconsistency. If IR is < 0.1, then the inconsistency is considered to be tolerable. If IR is > 0.2, then a re-examination of the judgments should be made, to ascertain whether they are still acceptable. It is important to emphasize, however, that the objective is to make good decisions, not to minimize the IR. Good decisions are most often based on consistent judgments, but the converse is not necessarily true.

D.4 Interpretation of Results

The results outputted from Expert Choice™ are all the figures in the form of horizontal black-bar-type histograms. These histograms provide the ranking, in order of decreasing importance, for the items being compared. The relative rankings are the calculated output using the pairwise comparisons made of the main and sub-criteria in the corresponding hierarchy models of Figures 1, 2 and 3. The labels on the left have their full name defined at the bottom of the histogram figures. The ranked items correspond to the lowest hierarchy level items of Figures 1, 2 and 3, as appropriate, which are shown with the cross-hatched borders. The accuracy of these rankings shown by the histogram length and also indicated as a fraction of a total of unity should not be assumed to be as good as the three-figure accuracy quoted on the left of the histogram display. The numerical rankings are more realistic, however, than an intuitive approach would provide. The three figure accuracy is available because some applications may input numerical data for comparisons, where the full accuracy can be justified.

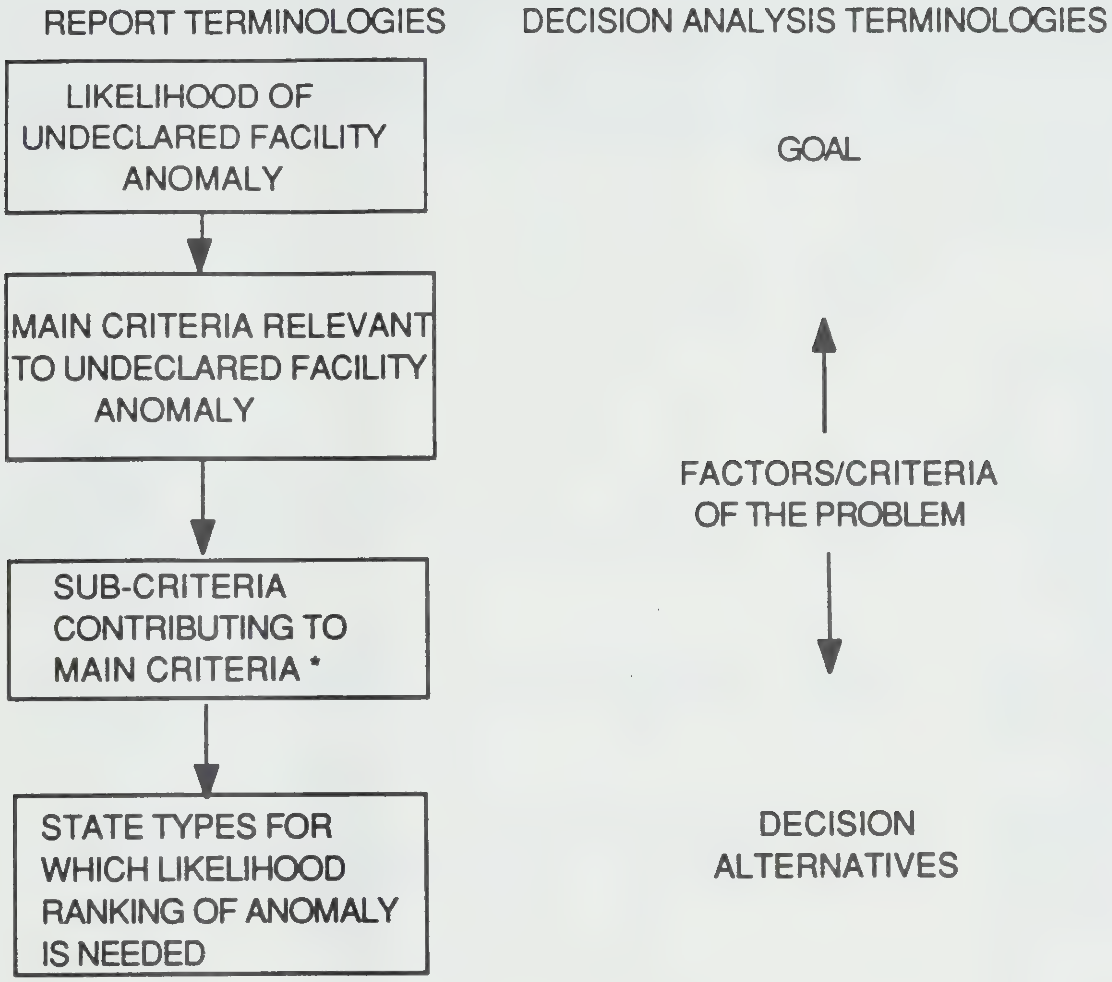
Complete details on the pairwise assessments and the weightings of the main and sub-criteria derived are not included in the report. This data is available from the author.

D.5 References

[D1] Expert Choice™ Inc., 4922 Ellsworth Avenue, Pittsburgh, PA, 15213.

[D2] T. Saaty, Multi-Criteria Decision Making. The Analytic Hierarchy Process, University of Pittsburgh, 1988.

[D3] T. Saaty, A Note on Decision Making and Number Crunching. Is Normalization the Answer ?, P.17 of Addenda for [A.1].



* Note: sub-criteria can be divided into more detailed levels of sub-criteria, if required.

Figure D.1 Simplified Schematic of Decision Analysis Structure Requirements

Table 1.1 Diversion Path Analysis: Generic Route: U-235, Declared Civilian, Dual-Purpose and Dedicated Nuclear Weapon Facilities

POTENTIAL FACILITY / SOURCES OF MATERIALS		URANIUM MINE	URANIUM MILLING	URANIUM CONVERSION	URANIUM ENRICHMENT FACILITIES						RESEARCH TEST REACTOR/ ISOTOPE PROGRAM USING HEU	ENRICHED URANIUM CONVERSION: FUEL FABRICATION FACILITIES	NAVAL PROPULSION REACTOR		EXISTING STOCKPILES
RISK RELEVANT PARAMETERS					Electromagnetic Separation (UCl4/calutron)	Gaseous Diffusion (UF6) [1]	High Speed Gas Centrifuge (UF6)	Laser Separation Methods [2]	Chemical Exchange Methods [3]	Aerodynamic Separation Methods [4]			Submarine [5]	Surface Vessel [5]	
LIKELIHOOD OF FACILITY ANOMALY (L)	NWS	low	low	low	Figure 1.1.1a	Figure 1.1.1b	Figure 1.1.1c	medium	low	low	very low	high	low	low	high
	NNWSD	low	low	low	Figure 1.1.1a	Figure 1.1.1b	Figure 1.1.1c	medium	low	medium	medium	high	low	low	high
	NNWSU	high	high	high	Figure 1.1.1a	Figure 1.1.1b	Figure 1.1.1c	very low	very low	medium	medium	high	no undeveloped states with technology	no undeveloped states with technology	low
IMPORTANCE OF FACILITY ANOMALY TO FINAL MATERIAL ACQUISITION (I)		low	low	medium	high	high	high	medium (NWS, NNWSD): low (NWS)	low, (technology not developed)	high	high	high	medium	medium	high
DIVERSION SIGNATURES		·ore quantity accountancy, 100kg HEU requires 20tons ore at 0.1% U with 0.2% U tails (100 tonnes ore per year needed for a 1000MWe reactor)	·accountancy anomalies in product shipments	·accountancy of product shipments ·production of a final chemical form which is not used in declared facility	·reconfiguration for high enrichment capacity is easier than diffusion plant -clean out frequency of collectors -detection of HEU on collectors -depleted U tails assay.	·rearrangemant of piping: changing/adding stages from parallel to series ·batch recycle mode changes plant operations ·HEU presence in final stages ·depleted U tails assay	·refeed of product to cascade ·power consumption changes ·rearrangemant of piping: changing/adding stages from parallel to series ·replacement/ speed change of centrifuge ·feed flow rate changes	·unknown	·unknown	·batch recycling	·fuel management scheme accountancy ·fresh/spent-fuel accountancy	· product enrichment, chemical form assay	·refuelling frequency ·fresh/spent fuel accountancy ·enrichment of spent fuel	·refuelling frequency ·fresh/spent fuel accountancy ·enrichment of spent fuel	·intelligence information
VERIFICATION METHODS	Technical Means	·remote/local optical surveillance not too useful, as difficult to identify or quantify extent of diversion	·local camera surveillance very limited effectiveness	·local camera surveillance very limited effectiveness	·local camera surveillance to detect production process operations ineffective as process not too visible	·local camera surveillance to detect configuration changes in process stages	·local camera surveillance to confirm interconnection status of centrifuges	·unknown	·unknown	·unknown	·local camera surveillance on fuelling operations and fresh/spent-fuel storage	·none very effective	·local camera surveillance on fresh/spent-fuel storage	·local camera surveillance on fresh/spent-fuel storage	·local camera surveillance of stockpiles
	Routine Inspections	·ore quantity accountancy not too useful, due to varying ore contents and large volumes involved	·product drum shipment accountancy ·product drum seals possible but large quantities involved ·product assay inconclusive	-conversion facility shipment accountancy ·product seal verification ·chemical product assay verification ·weighing of UF6 cylinders	·on-line gas phase enrichment monitor (for feed, product and tails) ·materials balance accountancy	·non destructive enrichment monitoring of feed, product and scrap ·materials balance accountancy ·sampling of feed, product and tails ·visual inspection of piping configuration	·non-destructive enrichment monitoring of process piping content ·materials balance accountancy ·sampling of feed, product and tails	·non-destructive enrichment monitoring ·materials balance accountancy (assay/ enrichment), details unknown	·materials balance accountancy (assay), details unknown	·equilibrium time between that of GD and GC materials balance accountancy (assay), details unknown	·fresh/spent fuel materials balance accountancy (assay)	·materials balance accountancy ·non-destructive enrichment monitoring	·materials balance accounting of spent fuel ·refuelling outage frequency ·spent-fuel containment seals	·same as adjacent left	·stockpile materials balance accountancy ·seal inspection (initial and periodic) ·non-destructive assay verification
	Special Inspections	·SI's have no advantages over routine inspections	·SI's have no advantages over routine inspections	·SI's have no advantages over routine inspections, due to time scale of process operation	·SI's limited value, due to time scale of process operation	·design /operation of plant designed for LEU is inflexible for HEU (batch recycling) operation, routine inspections adequate ·process equilibrium time ≈weeks ·SI limited value	·SI's limited value	·would depend on adequacy of RI's	·would depend on adequacy of RI's	·would depend on adequacy of RI's	·SI's limited value	·SI's for enrichment monitoring	·SI's limited value	·SI's limited value	·SI's limited value
EFFECTIVENESS OF VERIFICATION METHODS		·not very effective, due to large ore quantities also needed for civilian reactors and monitoring of varying ore concentrations	·not very effective, due to shipment quantities, no. of drum seals and possibility of previously hidden stockpiles	·assay effective for diversion of undeclared compound type for undeclared facility, not very effective for potential diversion to a declared enrichment facility	·RI's should be conclusive ·SI's limited value	·if facility designed for LEU routine inspections are conclusive	·RI's should be conclusive ·SI's limited value	·inadequate information to date	·inadequate information available	·inadequate information available	·RI's should be effective	·RI's should be conclusive	·RI's, fuel accountancy should be adequate	·RI's, fuel accountancy should be adequate	·RI should be conclusive, if storage locations fixed
RISK OF DIVERSION (L x I)		See Figure 2 for the risk ranking hierarchy variables and Figures 2.1.1a, b and c for the relative rankings for NWS, NNWSD and NNWSU, respectively.													
	NWS	10	11	12	9	13	8	2	4	5	6	3	7	7	1
	NNWSD	11	12	13	9	10	6	1	5	2	7	4	8	8	3
	NNWSU	9	10	11	1	7	2	8	12	3	6	4	N/A	N/A	5

[1] Mass diffusion and thermal diffusion facilities are omitted as there are no declared facilities of these types. Thermal diffusion, a demonstrated method, is listed under undeclared U-235 facilities, Table 2.1

[2] There are two main laser isotope separation techniques; molecular and atomic vapour. No distinctions are made between them for the purposes of this analysis.

[3] There are two main methods; solvent extraction and ion exchange. No distinctions are made between them for the purposes of this analysis. Risk rankings imply all types of R &D enrichment facilities

[4] A large number of aerodynamic isotope separation techniques are possible. The demonstrated Helikon method is implied here

[5] These facilities also imply the fresh and spent-fuel handling and storage locations, as well as the vessels

Table 1.2 Diversion Path Analysis: Generic Route Pu-239, Declared Civilian, Dual Purpose and Dedicated Nuclear Weapon Facilities

POTENTIAL FACILITY / SOURCES OF MATERIALS		URANIUM MINE	URANIUM MILLING	URANIUM CONVERSION	CIVILIAN POWER REACTOR	DUAL-PURPOSE REACTOR	MILITARY PRODUCTION REACTOR	RESEARCH & TEST REACTORS	PLUTONIUM REPROCESSING [1]		PLUTONIUM CONVERSION/ FUEL FABRICATION FACILITY	EXISTING STOCKPILES
RISK RELEVANT PARAMETERS									Chemical	Laser Isotope Separation		
LIKELIHOOD OF FACILITY ANOMALY (L)	NWS	low	low	low	low, (pressure vessel); high (channel type)	high	low (assumed shutdown)	low (< 10 MW,LEU fuelled); medium (> 10 MW, D20 moderated, with in-core loop facilities)	high	technology under development (US had proposed plant)	high	high
	NNWSD	low	low	low	as above	high	N/A	as above	high	low	high	high
	NNWSU	low	low	low	as above	N/A	N/A	high	high	low	high	low
IMPORTANCE OF FACILITY ANOMALY TO FINAL MATERIAL ACQUISTION (I)		low	low	low	as above	high	high	high, depending on reactor rating and neutron flux	high	very low	medium	high
DIVERSION SIGNATURES		Same as for see Table 2.1			•Modification of fuelling scheme for Pu-239, fuelling frequency changes (pressure vessel)	•Frequency of shutdowns if off power refuelled	•Thermal emissions indicating operation	•Fuelling scheme changes •Active experimental loop program.	• Active liquid waste tank storage •Active gaseous emissions	•EM emissions from lasers (not yet demonstrated)	•Small size chemical plant, not distinctive •Active emissions small	•Intelligence information
VERIFICATION METHODS	Technical Means	Same as for see Table 2.1			•Film/video camera surveillance of fueling operations (channel reactor) and spent-fuel storage •bundle counters (channel reactors)	•Film/video camera surveillance of spent-fuel storage	•Satellites detecting thermal infra-red radiation for S/D reactors. •non-intrusive facility seals	•Camera surveillance of fresh and spent-fuel storage	•camera surveillance of bulk fuel shipment receipts	•camera surveillance of bulk fuel shipment receipts	•none defined, camera surveillance of fuel receipts not effective	•camera surveillance of stockpiles
	Routine Inspections	Same as for see Table 2.1			•seals (pressure vessel reactors) •fresh and spent fuel seal inspections •no practical direct assay method of Pu content in spent-fuel bay •fresh and spent-fuel accountancy	•Same as for civilian reactors	•Facility seal inspections (reactors assumed shutdown) •Spent fuel seal inspections	•Spent & fresh-fuel seal inspections •fresh and spent-fuel accountancy	•Inventory change verification: spent fuel receipts, waste streams, Pu product output, Pu shipments •Operations verification: transfers to cells,shearing,dissolution, instrumentation •Design verification •Interim & physical inventory verification	•specific techniques unknown •design, inventory & operations verification expected as for chemical reprocessing	•Inventory change verification: Pu nitrate receipts, Pu metal product, waste streams	•stockpile accountancy •seal inspection •assay verification
	Special Inspections	Same as for see Table 2.1			SI limited value	SI limited value	SI limited value	SI limited value	Plant complexity, inventory holdups, time scales makes high SI confidence difficult	•Disclosure of technology and process needed	SI limited value	•effective with assay verification
EFFECTIVENESS OF VERIFICATION METHODS		Same as for see Table 2.1			RI conclusive	RI conclusive	TM and RI conclusive	RI conclusive	Complexity of process makes RI essential and difficult to be conclusive	•Unknown	•RI conclusive	•RI should be conclusive, if storage locations fixed
RISK OF FACILITY DIVERSION (L x I)		See Figure 3 for the risk ranking hierarchy, and Figures 3.1.2a, b and c for relative risk rankings for NWS, NNWSD and NNWSU, respectively. Ranking order also given below for reference.										
	NWS	7	8	9	6	3	5	4	2	no facilities	2	1
	NNWSD	6	7	8	5	4	9	3	2	no facilities	2	1
	NNWSU	4	5	6	3	8	9	1	2	no facilities	2	7

[1] Safeguards at a reprocessing plant depend significantly upon the scale and design features of the plant; e.g, a small plant with manual controls will require very different safeguards than a large new commercial-scale plant.

Table 1.3 Diversion Path Analysis: Generic Route: U-233, Declared Civilian, Dual Purpose and Dedicated Nuclear Weapon Facilities

POTENTIAL FACILITY / SOURCES OF MATERIALS / RISK RELEVANT PARAMETERS		THORIUM MINING	THORIUM MILLING	THORIUM CONVERSION	CIVILIAN POWER REACTOR	DUAL PURPOSE REACTOR	MILITARY PRODUCTION REACTOR	RESEARCH & TEST REACTORS	THORIUM REPROCESSING	THORIUM CONVERSION	EXISTING STOCKPILES
LIKELIHOOD OF FACILITY ANOMALY (L)	NWS	low	low	low	low, (pressure vessel); medium (channel type)	low	low	low (< 10 MW, LEU fuelled); medium (> 10MW, D20 moderated with in-core experimental facilities)	high	high	high
	NNWSD	low	low	low	as above	low	low	as above	high	high	high
	NNWSU	low	low	low	as above	medium	medium	as above	low	low	very low
IMPORTANCE OF FACILITY ANOMALY TO FINAL MATERIAL ACQUISITION (I)		high	low	low	low	high	high	high	high	high	high
DIVERSION SIGNATURES		•Ore shipment accountancy indicators	•Accountancy anomalies in product shipments	•Accountancy anomalies in product shipments	•Modification of fuelling scheme for U-233	•Modification of fuelling scheme for U-233	•Thermal emissions indicating operation	•Fuelling scheme •Active experimental isotope production program.	• Active liquid waste tank storage •Active gaseous emissions	•Small chemical plant, not distinctive •Active emissions small	•intelligence information
VERIFICATION METHODS	Technical Means	•Same as for equivalent data for uranium, see Table 1.1			•Same as for see Table 1.2				•camera surveillance of bulk fuel shipments	•none defined	•camera surveillance of stockpiles
	Routine Inspections	•ore quantity and grade accountancy	•accountancy anomalies in product shipments	•accountancy anomalies in product shipments	•Facility camera surveillance of fuelling operations/spent fuel seals	•Facility camera surveillance of fueling operations/ spent fuel seals	•inspection seals on reactor vessel	•spent fuel accountancy/ spent fuel seals	•accountancy	•accountancy	•stockpile accountancy •seal inspection •assay verification
	Special Inspections	•Same as for equivalent data for uranium, see Table 1.1			•Same as for see Table 1.2				•Detection of thorium conclusive	•Detection of thorium conclusive	•assay verification
EFFECTIVENESS OF VERIFICATION METHODS		•Same as for see Table1.1			•Same as for see Table 1.2				•SI conclusive	•SI conclusive	•Conclusive as stockpiles small
RISK OF DIVERSION (L x I)		Figure 3 gives risk ranking hierarchy. Relative rankings are similar to Figures 3.1.2a, b, c for equivalent declared Pu-239 facilities. Absolute risk will be much less than Pu-239.									
	NWS	7	8	9	6	3	5	4	2	2	1
	NNWSD	6	7	8	5	4	9	3	2	2	1
	NNWSU	4	5	6	3	8	9	1	2	2	7

Table 2.1 Diversion Path Analysis: Generic Route: U-235, Undeclared Facilities

POTENTIAL FACILITY /SOURCES OF MATERIAL		URANIUM MINE	URANIUM MILLING	URANIUM CONVERSION	URANIUM ENRICHMENT FACILITIES							RESEARCH/ TEST REACTOR/	ENRICHED URANIUM CONVERSION/	EXTRACTION FROM IRRADIATED ENRICHED FUEL	SMUGGLED URANIUM MATERIALS			EXISTING STOCKPILES
RISK RELEVANT PARAMETER					Electromagnetic separatio (UCl4/calutron)	Thermal Diffusion (UF6)	Gaseous Diffusion (UF6)	High Speed Gas Centrifuge (UF6)	Laser Separation Methods	Chemical Exchange Methods	Aerodynamic Separation Methods	ISOTOPE PROGRAM USING HEU	FUEL FABRICATION FACILITY		Natural Uranium Ore	Raw Enriched Uranium Compounds	Refined Weapon Grade Material	
LIKELIHOOD	NWS	low	low	low	Fig.1.2.1a	low	Fig.1.2.1b	Fig.1.2.1c	Fig.1.2.1d	low	low	medium	low	low	low	low	low	high
OF FACILITY	NNWSD	low	low	low	Fig.1.2.1a	low	Fig.1.2.1b	Fig.1.2.1c	Fig.1.2.1d	low	low	medium	low	medium	low	low	low	low
ANOMALY (L)	NNWSU	high	high	high	Fig.1.2.1a	high	Fig.1.2.1b	Fig.1.2.1c	Fig.1.2.1d	low	low	low	high	low	high	high	high	very low
IMPORTANCE OF FACILITY ANOMALY TO FINAL MATERIAL ACQUISITION (I)		low	low	medium	high	medium (useful as an LEU feed)	medium	high	high	low (R&D stage, France/Japan)	high	low	medium	low	low	high	very high	high
DIVERSION SIGNATURES		-Transportation, personnel, infrastructure needs -large tailings piles -If solution mining, tailings piles not large but large number of well drillings -Phosphate mining activity (tailings more significant than for U-ore mine as ore ≈0.01%U) -Airborne and surface radioactivity levels -waste water discharges high for open pit mining	-Large size of mill and tailings piles/ ponds (1Mg of U-235 from 0.1% uranium ore produces ≈ 200,000 tonnes leached ore) -usually located close to mine -transport activity if remote from mine	-Medium size chemical reprocessing buildings with liquid wastes -use of HF	-Large power supply needed per plant area. -Large amount of cooling. -Medium size chemical reprocessing with liquid effluent wastes (organics, acids) -Depleted U tails storage -Large number (hundreds) of calutrons needed	-Large plant size but much smaller than GD, high steam volume consumption -Large electrical supply for pumps/compressors -No known facilities currently operating -liquid effluents	- Extremely large plant size (few hectares) -extremely large electrical power supply and cooling (river or towers) -depleted U tails storage -security fencing -air defence systems	-Plant size large (≈ few thousand sq.m) but much less distinctive (≈1/10) than for GD. - Large manufacturing effort to produce large numbers of centrifuges -security fencing -air defence systems	-20 years of R & D in U.S. France and Israel have an unknown R&D status. -Plant smaller than for centrifuges. -High power laser operations	-Still at R & D stages -Plant size and power supplies similar to GC -large volumes of specialized chemicals and uranium holdup in Chemex method	-Plant size intermediate between GD and GC -Large power supplies for compressors	-physical size and structural features -thermal emissions -security fencing -gaseous/ liquid active emissions -air defenc systems	-Small size chemical plant, not distinctive	-Very likely located close to a reactor site -active liquid and gaseous wastes	-Material transportation shipments involve large volumes	-Involves small volumes of material -materials & equipment export control information	-Involves small volumes of material -materials & equipment export control information	-Intelligence information
VERIFICATION	Technical Means	-Optical and infra-red satellite reconnaissance -Atmospheric and surface radioactivity remote monitoring	-Optical and infra-red satellite reconnaissance -Atmospheric and surface radioactivity remote monitoring	-Chemical/ radiological gaseous emissions minimal, remote monitoring not conclusive	-Optical and infra-red satellite reconnaissance	-Optical and infra-red satellite reconnaissance	-Optical and infra-red satellite reconnaissance	-Optical and infra-red satellite reconnaissance	- Satellite detection of EM signals from high power pulsed laser emissions possible in principle.	-Unknown, possibly chemical waste storage indication	-Optical and infra-red satellite reconnaissance	-Infra-red & optical satellite reconnaissance	-Chemical, nuclear emissions environmental monitoring	-Possibly active emission monitoring	-Intelligence information	-Intelligence information	-Intelligence information	-none
METHODS	Routine Inspections	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Special Inspections	TM adequate, SI not needed providing phosphate or other end use can be discounted	TM adequate, SI not needed providing phosphate or other end use can be discounted	U conversion process easy to confirm in-situ presence of HF and UF6 or UCl4	Needed to confirm TM	Needed to confirm TM	TM should be adequate	Needed to confirm TM	Needed to confirm TM	Likely needed to confirm TM	Likely needed to confirm TM		Needed to confirm TM	Needed to confirm TM	N/A	N/A	N/A	N/A
EFFECTIVENESS OF VERIFICATION METHODS		TM may be conclusive if non-uranium end use is discounted; facility and infra-structure sizes difficult to disguise even if refined U quantity is modest	TM may be conclusive if non-uranium end use discounted, tailings piles/ ponds distinctive even if refined U quantity is modest	TM not conclusive, SI confirmation needed	TM not conclusive	TM not conclusive	TM conclusive	TM Inconclusive	TM verification confidence unknown	SI needed	SI needed	TM conclusively identifies facility -SI needed to confirm diversion	SI needed	SI needed	-Depends on intelligence, should be conclusive	-Depends on intelligence	-Depends on intelligence	-Ineffective for NWS if large size of hidden stockpiles
		See Figure 2 for the risk ranking hierarchy and Figure 2.2.1a, b, c for the relative risk rankings for NWS, NNWSD and NNWSU respectively and below for ranking order																
RISK OF FACILITY	NWS	8	9	10	13	11	14	6	2	3 (+other R&D)	4	15	4	15	14	12	7	1
DIVERSION (L x I)	NNWSD	9	10	11	7	12	14	4	1	2 (+other R&D)	5	16	5	16	15	13	8	3
	NNWSU	9	10	11	3	7	15	4	1	13	6	16	6	16	8	2	1	14

Table 2.2 Diversion Path Analysis: Generic Route Pu-239, Undeclared Facilities

POTENTIAL FACILITY / SOURCES OF MATERIALS		URANIUM MINE	URANIUM MILL	URANIUM CONVERSION	POWER/DUAL PURPOSE/ PRODUCTION REACTOR	RESEARCH/ TEST REACTOR	PU ENRICHMENT	PU REPROCESSING FACILITY	SMUGGLED PLUTONIUM MATERIAL		EXISTING STOCKPILES
RISK RELEVANT PARAMETERS							(LASER ISOTOPE SEPARATION)		IRRADIATED FUEL	PU EXTRACTED FROM FUEL	
LIKELIHOOD	NWS	low	low	low	very low	very low	Proposed special isotope separation plant cancelled (US)	low	very low	very low	high
OF FACILITY	NNWSD	low	low	low	very low	very low	very low	medium	very low	very low	low
ANOMALY (L)	NNWSU	high (if state has research reactor)	high	high	power reactor only	high	very low	high	low	high	very low
IMPORTANCE OF FACILITY ANOMALY TO FINAL MATERIAL ACQUISITION (I)		low	low	low	high	high	very low	high	low	high	high
DIVERSION SIGNATURES		Same as for see Table 2.1			•physical size & structural features •security fencing •thermal emissions •electrical transmission network •gaseous/liquid active emissions	•physical size & structural features •security fencing •air defence systems •thermal emissions •gaseous/ liquid active emissions	•EM laser emissions? •building type and size not distinguishable?	•radioactive discharges (I-129, Kr-85) •active liquid waste tank storage	•heavy/large containers need for storage and transport •fuel is self-protected by theft by high activity •export controls information	•Pu activity from reprocessed fuel not a large problem •export controls information	•intelligence information
VERIFICATION METHODS	Technical Means	Same as for see Table 2.1			•infra-red & optical satellite reconnaissance	•infra-red & optical satellite reconnaissance	•remote EM detection (not demonstrated to date?)	•remote monitoring/ sampling of airborne activity and liquid discharges	•intelligence information	•intelligence information	•satellite reconnaissance observation of storage location shipment transfers
	Routine Inspections	N/A			N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Special Inspections	Same as for see Table 2.1			•physical inspection provides confirmation of size, design type specifics •radiation monitoring confirms current production status •spent fuel storage inspection indicates past production	•physical inspection provides confirmation of size, design type specifics •radiation monitoring confirms production status •spent fuel storage inspection indicates past production	•physical inspection and assay measurements needed to confirm purpose •divulgence of design & operational knowledge needed to assess capability	•physical inspection and divulgence of design & operational knowledge needed to assess capability	•Interception required to confirm	•Interception required to confirm	•physical inspection and portable radiation monitoring to confirm Pu
EFFECTIVENESS OF VERIFICATION METHODS		Same as for see Table 2.1			•TM conclusively identify facility •SI verifies actual diversion conclusively	•TM conclusively identify facility •SI verifies actual diversion conclusively	•SI needed to confirm purpose and capability	•TM conclusively identify purpose •SI identifies capability	•Interception required to confirm	•Interception required to confirm	•TM not conclusive
RISK OF DIVERSION (L x I)		See Figure 3 for risk ranking hierarchy and Figures 3.2.2a, b and c for the relative risk rankings for NWS, NNWSD and NNWSU respectively									
	NWS	8	9	10	2(DP) 5(POW) 7(PROD)	4	12	3	11	6	1
	NNWSD	8	9	10	2(DP) 5(POW) 8(PROD)	4	12	3	11	7	1
	NNWSU	7	8	9	4(POW)	3	10	2	6	1	5

Table 2.3 Diversion Path Analysis: Generic Route U-233, Undeclared Facilities

POTENTIAL FACILITY / SOURCES OF MATERIALS		THORIUM MINING	THORIUM MILLING	THORIUM CONVERSION	POWER/DUAL PURPOSE/ PRODUCTION REACTOR	RESEARCH & TEST REACTORS	THORIUM REPROCESSING	THORIUM CONVERSION	SMUGGLED THORIUM CYCLE MATERIALS			EXISTING STOCKPILES
RISK RELEVANT PARAMETERS									Thorium Ore	Purified Thorium Compounds	Weapon Grade U-233	
LIKELIHOOD OF FACILITY ANOMALY (L)	NWS	low	low	low	high	low (< 10 MW, LEU fuelled); medium (> 10 MW, D20 moderated HEU fuelled, in-core experimental facilities, high (HEU used in isotope production)	low	low	low	low	low	high
	NNWSD	low	low	low	high	as above	low	low	low	low	low	very low
	NNWSU	high	high	high	low	as above	medium	medium	high	medium	high	very low
IMPORTANCE OF FACILITY ANOMALY TO FINAL MATERIAL ACQUISITION (I)		high	low	low	high	medium, depending on reactor rating and neutron flux	high	high	low	high	low	medium
DIVERSION SIGNATURES		•extracted from phosphate, monazite sands and uranium mining operations; other signatures as per Table 2.1	•Same as for see Table 2.1	•Medium size chemical reprocessing buildings with liquid wastes	•Same as equivalent Pu-239 facilities, see Table 2.2		•active discharges •active liquid waste tank storage	•small size chemical plant not distinctive •active emissions small	•material transportation shipments involve large volumes	•transportation involves small volumes of material	•transportation involves small volumes of material •radiation shielding needed	•intelligence information
VERIFICATION METHODS	Technical Means	•Same as equivalent Pu-239 facilities, see Table 2.1			•Optical and infrared satellite reconnaissance	•Optical and infrared satellite reconnaissance	•remote environmental radioactive release monitoring	•not suitable	•intelligence information	•intelligence information	•intelligence information	•none
	Routine Inspections	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Special Inspections	•Needed to confirm thorium content	•Needed to confirm thorium separation/ concentration from ore	•Needed to confirm production of thorium and fuel fabrication process	Same as equivalent Pu-239 facilities, see Table 2.2		•U-333 analysis conclusive	•U-333 analysis conclusive	•interception required to confirm	•interception required to confirm	•interception required to confirm	•physical inspection and portable radiation monitoring to confirm Th-233
EFFECTIVENESS OF VERIFICATION METHODS		Intent of thorium diversion could not be confirmed without mill process special inspection, unless other uses of ore could be discounted	SI needed to confirm separation of thorium	TM not conclusive, SI confirmation needed	Same as equivalent Pu-239 facilities, see Table 2.2		SI needed	SI needed	•Depends on intelligence sources	•Depends on intelligence sources	•Depends on intelligence sources	•ineffective, hidden stockpiles likely small size
RISK OF DIVERSION (L x I)		Figure 3 gives risk ranking hierarchy. Relative rankings similar to those of Figures 3.2.2a, b and c for the equivalent declared Pu-239 facilities. Absolute risk will be much less than for Pu-239.										
	NWS	8	9	10	2(DP) 4(POW) 6(PROD)	4	3	3	7	5	5	1
	NNWSD	9	10	11	2(DP) 5(POW) 6(PROD)	4	3	3	8	7	7	1
	NNWSU	6	7	8	4(POW)	3	2	2	3	1	1	5